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Air Pollution

CALCULATING FUTURE CARBON MONOXIDE EMISSIONS AND CONCENTRATIONS FROM URBAN TRAFFIC DATA

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CALCULATING FUTURE CARBON MONOXIDE EMISSIONS AND CONCENTRATIONS FROM URBAN TRAFFIC DATA

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U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

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FOREWORD

The basic goal of this study was to test the feasibility of an urban area approach for calculating carbon monoxide emissions and concentrations from traffic data. That the method provided reasonable results and that the bulk of this report is devoted to a discussion of these results attests to the success of the approach. However, it should not be assumed that the approach is now ready to be applied to a variety of other cities; the authors caution that many of the steps in the approach and the underlying assumptions should best be further examined and refined. This report is intended not primarily as an end in itself but as a starting point for future efforts.

ABSTRACT

An urban area approach was applied in Washington, D. C., to calculate present and future emissions and ambient concentrations of carbon monoxide. Calculations were based on 1964 and projected 1985 traffic volumes, emission factors, and a meteorological diffusion model. The following findings were obtained: 1) With no emission control, the total carbon monoxide emitted in Washington will approximately double in a non-uniform manner; the smallest increases will occur downtown and the greatest increases at the outskirts. 2) The principal effect of such nonuniformity, also apparent in Chicago, is to increase the area of the city exposed to high emission densities, leading to consequent increases in the area over which concentrations occur. 3) The change in concentrations experienced at one site is influenced more by the emission pattern of the entire urban area than by changes in the immediate vicinity of the site. 4) Without control, the mean annual concentrations at four varied sites in Washington would range from 2.2 ppm to 11 ppm in 1985, representing increases from 44 percent to 69 percent over 1964 values. 5) With 50 percent control, the 1985 concentration at the CAMP station will be 15 percent less than the 1964 value, and values at the other sites will drop from 21 percent to 29 percent. 6) Concentrations calculated for the weekday peak-traffic period (6 to 8 AM) show two-hour average concentrations in 1985 ranging from 1.6 ppm to 25 ppm for various meteorological conditions, representing increases from 40 percent to 120 percent over the 1964 values. 7) Even with 50 percent control, some peak-traffic-period concentrations will increase 10 percent for certain meteorological conditions.

CALCULATING FUTURE CARBON MONOXIDE EMISSIONS AND CONCENTRATIONS FROM URBAN TRAFFIC DATA

INTRODUCTION

The endless proliferation of the automobile suggests to many observers that gaseous exhaust products may increase without limit, especially in ever-expanding urban areas. Measurable carbon monoxide concentrations are usually traced to traffic flow, since the primary source of carbon monoxide is vehicle exhaust. Because of the biologically hazardous nature of carbon monoxide,[1] it is important to determine how traffic patterns in the urban environment will affect carbon monoxide emissions and concentrations.

A number of urban areas throughout the country have developed detailed projections of future traffic patterns for use in city planning. To evaluate the effect of changing traffic patterns on carbon monoxide levels, it is necessary to develop a method for calculating carbon monoxide emissions and concentrations from such traffic data. Such an approach should be directed toward answering two questions:

1. How are the emissions distributed throughout the urban area -- both now and in the future?

2. At various points, what average yearly and hourly concentrations -- both present and future -- will result from these emissions?

This report describes an urban area approach by which traffic data provided by traffic planning agencies can be used to derive estimates of carbon monoxide emissions and their geographical distribution throughout the city; the estimates of emissions then can be used in a meteorological diffusion model to calculate carbon monoxide concentrations at several selected points.

This approach has been applied to Washington, D. C., where projected traffic data for 1985 were available. Comparing the 1985 and 1964 results provides the pattern of expected growth in emissions for different geographical regions and indicates the resulting increase in concentrations at selected points within the city. The pattern of emissions growth also has been briefly compared with that for Chicago.

THE METHOD

Preparing an Inventory of Emissions

In developing a technique for estimating carbon monoxide (CO) emissions, one must decide what kinds of emission data are needed. One approach, for example,

applies several relatively simple steps to arrive at the average daily emissions for the entire city. The average number of miles traveled by all vehicles on a single day is obtained from traffic authorities, and this figure is multiplied by a factor representing the amount of CO released by a vehicle -- on the average -- for each mile of travel. Applied to the Washington, D. C., metropolitan area, such calculations show that 1,150 tons of CO per day were released in 1964 and that -- based on projected traffic data -- emissions will climb to 2,170 tons per day in 1985. This approach leads to dramatic results, an increase in emissions of 89 percent, but it does not tell the whole story. During the 21-year span, the city will undergo a great expansion. The 2,170 tons emitted per day in 1985 will be distributed over a much wider area, and consequently will be diffused in a greater volume of air. This means that the increase in concentrations at particular points may bear no simple relationship to the increase in total emissions.

To be of optimum use, the emission data should (1) take into account the changes in area that will occur in the city, and (2) lend themselves to calculating the resulting concentrations with a meteorological diffusion model. Since the traffic varies greatly from one part of the city to another, emissions can be more adequately described if the urban area is divided into small segments, or zones, to allow comparisons among different geographical regions. The size and shape of the individual zones are not critical, although each zone should be small enough to show the differences in emissions at various locations in the city and large enough to avoid domination by unique or irregular features (lakes, parks, air terminals, etc.). For simplicity and ease of understanding, the zonal configuration should form a regular pattern, or grid, that can be superimposed over the map of the city.

The next step is to estimate the total emissions of CO from traffic for each zone in the grid. Each zone will enclose a number of routes and segments of routes, each of which will consist of many point sources of carbon monoxide -- vehicle tailpipes -- in continual movement. The amount of carbon monoxide released from each tailpipe per mile is a function of the average speed of the vehicle. Thus, to estimate the total daily emissions on a given route, one must know (1) the average velocity of the traffic, and (2) the total number of miles traveled by all vehicles during a day.

Most municipal traffic agencies provide large street maps showing the number of vehicles that travel each route or route segment on an average weekday, expressed as the average daily travel (ADT) or traffic volume. The total number of miles traveled on that route segment in an average weekday is usually expressed as daily vehicle-miles of travel (DVMT). To convert the ADT into DVMT, we multiply the ADT (number of vehicles per day) by the length of the route segment.

A 1962 study of exhaust emissions in two large cities[2] showed that carbon monoxide emissions per vehicle-mile decrease with increased speed, as shown in Figure 1. Most traffic authorities can provide information on the average speeds on various routes. Consequently, Figure 1 can be used to obtain a factor for converting vehicle-miles to emissions for each route. This emission factor can be used to obtain the emissions on any route, and by adding the emissions for all routes within a zone the zonal emissions can be obtained.

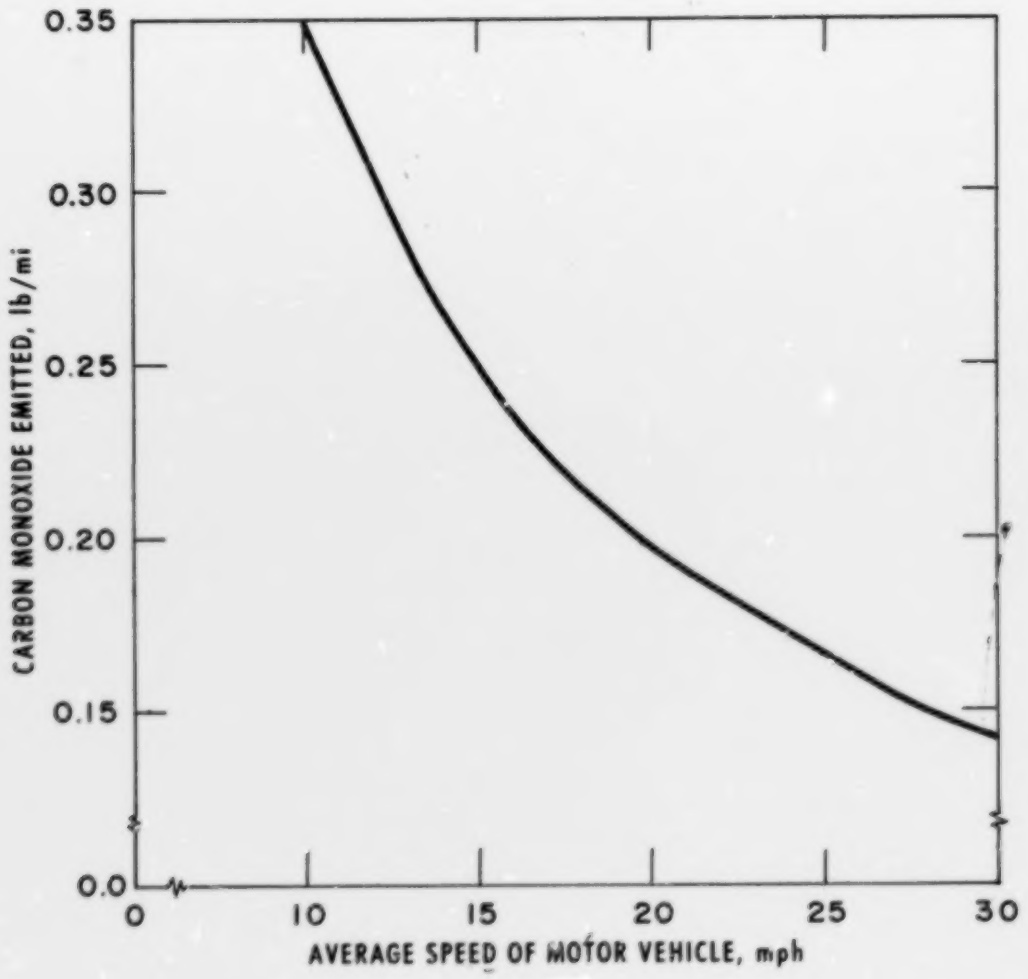


Figure 1. Emissions of carbon monoxide vs. vehicle speed.

SOURCE: A.H. Rose, Reference 2.

The preceding discussion outlines the development of a procedure for obtaining an inventory of CO emissions by geographical zones. The overall approach consists of five basic steps:

1. A uniform grid containing many small zones is superimposed on a street map of the city.

2. The average velocities and the daily vehicle miles of travel for individual routes are obtained from information provided by municipal traffic agencies.

3. Referring the average velocity to Figure 1 provides an emission factor, in pounds of CO per vehicle-mile.

4. Multiplying the daily vehicle-miles of travel by the emission factor gives the total emissions for the route or route segment.

5. Adding the emissions from all routes within a zone yields the total emissions for each zone.

Calculating Concentrations from Emissions: The Diffusion Model

The emissions inventory provides a summary of emissions throughout the city by geographical zones. It is useful to present this information in graphical form and to examine the trends in the growth of emissions by comparing the projected 1985 data with current data. However, the ultimate concern over pollution caused by motor vehicles relates not to emissions, but to the concentrations that result from these emissions. The concentration measured at any point is a function not only of the geographical distribution of sources surrounding the point but of the meteorological conditions responsible for diffusing the pollutant. To take into account source location (i.e., source-to-receptor distance) and meteorological variables, a mathematical diffusion model was applied to the data in the emissions inventory.

Annual Concentrations. The emissions were derived from average daily traffic, representative of traffic averaged over all weekdays of the year; and they are therefore daily average emissions. In applying the annual diffusion model, these emissions were incorporated with wind data representative of an average year to arrive at the mean annual carbon monoxide concentrations at several receptor sites. Since the long-term average meteorological data, say over a 10-year period, will not differ significantly from the average data for any other 10-year period, wind data averaged from 1951 to 1960 were used in the model as representative of an average year. The pertinent wind data are the frequencies of wind speed and direction, which are normally represented in a standard wind rose.

Pooler[4] developed an urban diffusion model that he applied to Nashville to calculate the mean monthly sulfur dioxide concentrations in considerable detail. To obviate the need for an electronic computer, a model much simpler than Pooler's was sought. Clarke[3] developed an urban diffusion model that permits rapid calculation of average hourly concentrations at a single receptor point. The latter model requires an estimate of the emissions in each of many segments of a wheel-shaped pattern, or overlay, centered on the receptor site. The diffusion model used in the present study* consists of a combination of Clarke's method for rapidly calculating concentrations with Pooler's method of estimating the vertical spread of the pollutant with time and wind speed and his use of standard wind rose data. The resulting model permits calculation of the mean annual concentration at a single point without an electronic computer.

In practice, the overlay--a wheel-shaped pattern with three concentric rings and eight radial sectors--is placed over a map of the city and centered on a receptor site. Then the emissions in each of its 24 segments are calculated. These emis-

*For a full discussion of the derivation of the model used in the present study, and its application, see Appendix A.

sion figures can be obtained from the summation of emissions from every route within a segment. To simplify this computation, however, the data from the emissions inventory (i.e., the table listing emissions for each zone of the inventory grid) were entered on a map containing the inventory grid, and the appropriate emission densities (emissions per unit area) were estimated by placing the overlay over the inventory grid and considering the partial areas of the grid zones contained within each overlay segment. The mean annual CO concentration at the receptor site (overlay center) was then calculated from the emission densities by use of the diffusion equations, which incorporate the segment-to-receptor distances and data on the frequencies of wind speed and direction.

Hourly Concentrations. Calculation of the mean annual concentrations provides only one data point for each year. More data points could be obtained if the calculated concentrations represented values averaged over a shorter time period, perhaps an hour. This would also provide more information on concentrations that are high in magnitude but of short duration.

An examination of the variation of urban traffic with time reveals that although the traffic volume varies considerably from hour to hour this diurnal variation is much the same for all weekdays of the year. Consequently, this typical diurnal pattern may be used to adjust average daily emissions to hourly values, and the resulting data can be considered applicable to any weekday of the year. A diffusion model may then combine wind data for a specific interval of time on a particular day with emission densities for the same period to arrive at an average concentration for those hours of that day. This permits the calculation of average hourly concentrations for different hours of the day and for any number of days of the year.

The data assembled in the emissions inventory are average daily emissions, because they were derived from the traffic of an average weekday. To convert these numbers to hourly values, the diurnal traffic pattern for the entire city can be assumed to apply to each zone. Although traffic in each zone reaches its morning peak at a slightly different time, the averaging interval was considered long enough that these variations could be ignored without serious error. The diffusion model used was the one developed by Clarke[3] for rapid calculation of the average hourly concentration at a single point. As mentioned previously, the annual diffusion model was derived in part from this average hourly model, and consequently, there are relatively few differences between the two: The hourly diffusion model uses wind data averaged over as brief a period as a single hour rather than standard wind rose data, and it uses a different method of estimating the vertical diffusion of the pollutant with time of travel and meteorological conditions.

Discussion. It is desirable, where possible, to compare concentrations calculated by the diffusion model approach with those actually observed. Any monitoring probe would have to be located at a specific point in the city--very likely a street--and the measurements would be influenced by traffic in the immediate vicinity. Of necessity, however, the diffusion model approach ignored this localized effect, because it was assumed that emissions are evenly distributed over the several-block area of each zone rather than concentrated in narrow routes bounded by buildings and other structures. Consequently, concentrations from a street-side sampling station

could be expected to be greater than concentrations calculated for the same site using the diffusion model. Although the traffic patterns for different streets are not exactly identical, the measured-to-calculated ratio for one such site probably could be used to convert the calculated concentrations for the other sites into data approximately comparable to a street-side measurement. This method was employed as part of the analysis of results.

Because of the above considerations and because some of the diffusion model premises cannot be completely tested, the numerical values of the calculated concentrations will always be open to some question. These problems were minimized, however, by comparing the results calculated for 1964 with those developed for 1985. The assumptions and constants are not likely to be different in 1985 than in 1964; hence, comparisons of the two sets of results developed from the same method are more valid than the absolute values of each set of results taken by itself. Thus the most valid approach in analyzing the results stresses the ratios between the two sets of numbers, emphasizing the changes and growth trends over the 21-year span.

APPLICATION OF THE METHOD: THE RESULTS

In 1965, the Bureau of Public Roads encouraged urban areas to begin developing total transportation projections based on population, land use, economic factors, etc. The Bureau also issued guidelines on the techniques to be used. Prior to this, however, many cities were already engaged in making such projections and they now have considerable data available for use.

Washington, D. C., is one of the cities that began its transportation study at an early date. This section draws on traffic data developed in that study to illustrate the application of the method by preparing an emissions inventory and calculating concentrations for the District of Columbia and the surrounding area.

The Emissions Inventory for Washington, D. C.

Authorities conducting the Washington Metropolitan Area Transportation Study were able to provide the traffic data necessary for preparing the emissions inventory. They supplied large traffic flow maps of Washington, D. C., and the surrounding area, showing future routes and projected average daily travel (ADT) for 1985. Maps showing traffic flow for 1964 were also available from the District of Columbia Department of Highways.

The zonal grid selected for the Washington emissions inventory is shown in Figure 2. It consists of five concentric rings, evenly spaced, and six radial sectors. A circular pattern was selected because urban areas usually grow from the center outward, and major routes often follow a concentric pattern. The square county boundary line was incorporated as part of the grid, making the outer edges somewhat irregular in pattern, but permitting the inclusion of Arlington county and a small portion of Alexandria. In addition, five more zones were added in a 2-mile-wide strip in Prince Georges and Montgomery Counties, Md., making a total of 40 zones in the grid.

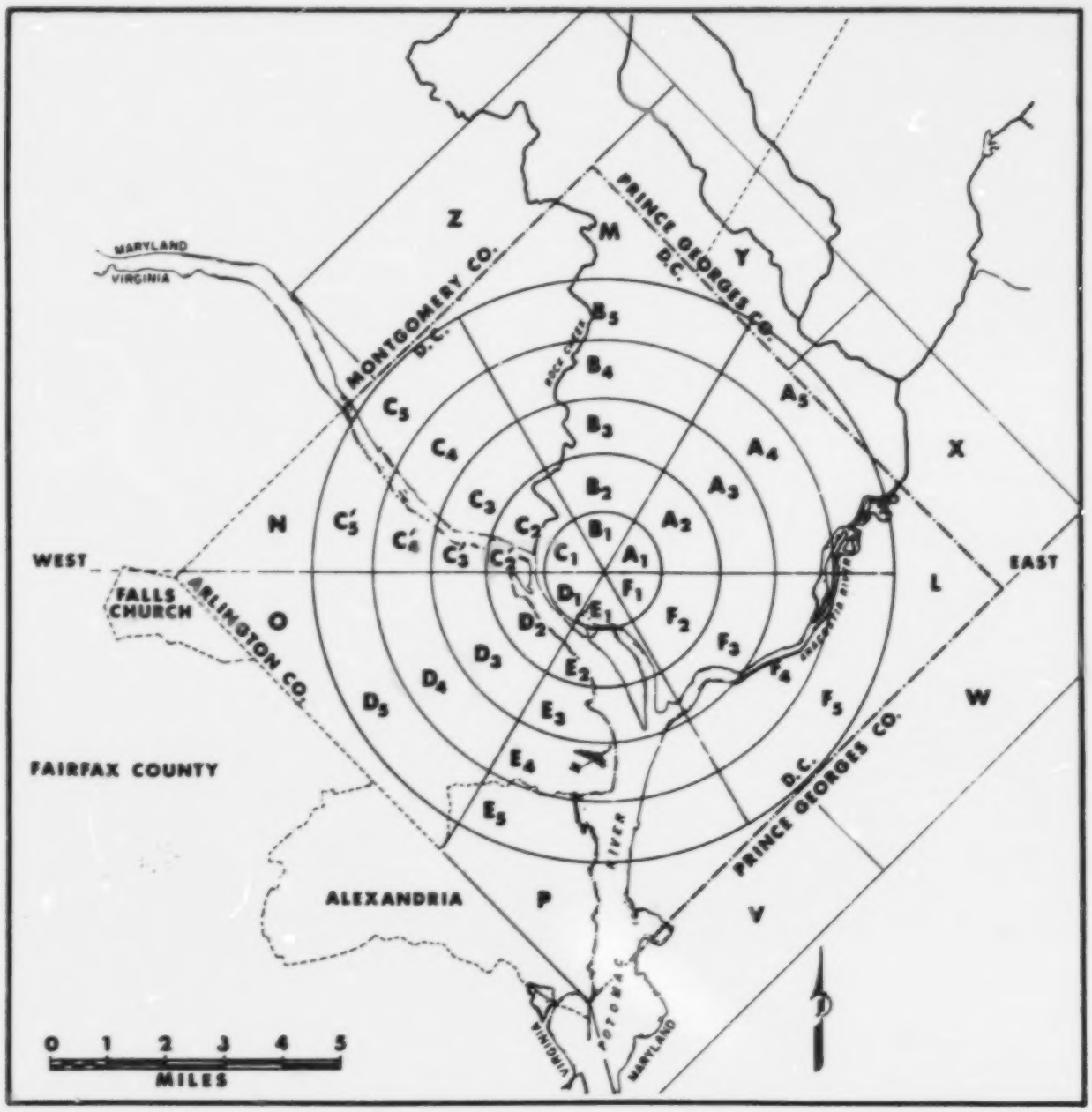


Figure 2. Zonal grid for Washington, D.C.

Ideally, such a predominantly circular pattern should be placed with its center at the center of the downtown area. In any given urban area, however, this point may be difficult to locate exactly. In Washington, the center of the pattern was placed at a point directly in front of The White House, on the northern part of The Ellipse, and the six sectors were aligned so that one radial boundary ran east-west.

Table 1 shows the completed emissions inventory, with listings for both 1964 and 1985. The zonal designations correspond to those in Figure 2. The emissions were estimated in the manner outlined on page 3. The traffic data were obtained by superimposing the grid on the large traffic flow maps provided by the Washington traffic agencies. Route distances within each zone were scaled by hand and multiplied by the average daily travel for the route. The results were added to give the average daily vehicle-miles traveled on all route segments within a zone. The process was carried out with 1964 maps and repeated with 1985 maps.

The average velocities used are also shown in Table 1. The values chosen were based on discussions with local traffic authorities and not on empirical data. Lacking better information, it was necessary to assume the same velocities would apply in 1985 as in 1964. A later examination of isochronal maps* suggested that the chosen velocities were high, on the average. The inverse relationship between emissions and average speeds (Figure 1) guarantees, therefore, that the emissions are underestimates of actual values.

Because the chief purpose of this report is to illustrate the methodology and its application, the effects of emission control devices are not included in the 1985 emission figures. The effect of such control devices can be found by multiplying the 1985 emission values by the average percentage control anticipated for 1985.

All the traffic data were listed in a traffic inventory,† with much the same format as Table 1, and the average velocities were employed to arrive at the emissions inventory of Table 1. The emission densities were obtained by dividing a zone's emissions by the zone's area; thus the emissions per unit area of different zones may be compared conveniently. The growth factors shown in the last column of Table 1 were computed by dividing the 1985 emission density by the 1964 figure. These factors provide an index of the growth in emissions for each zone. Since traffic data for Alexandria were unavailable, emission data for zones E_5 and P were not listed.

Geographical Trends in Emissions Growth

A pictorial description of the growth in CO emissions over the 21-year span is provided by Figure 3. Smooth isolines have been drawn to enclose areas with emission densities that equal or exceed a specified value. It is clear that the area over which the highest emissions occur increases greatly by 1985, based on a no-control situation. The mean emission density over the entire study area roughly doubles -- from about 16,000 to 30,000 pounds per day per square mile -- but the area over which densities equal or exceed 100,000 pounds per day per square mile increases about 7 times. The 60,000-pound isoline increases its enclosed area about 3 times,

*These maps show the required driving times, for various directions, to travel from the downtown area to the outskirts. They were supplied by the Traffic Survey and Analysis Section of the District of Columbia Department of Highways.

†The traffic inventory appears in Appendix B.

TABLE 1
Emissions Inventory for Washington, D. C.

Zone	Area,[a] mi^2	Average speed mph	Emission factor,[b] lb CO/mi	Emission rate lb CO/day, 1000's		Emission density lb CO/day-mi^2, 1000's		Growth factor 1985/1964
				1964	1985[c]	1964	1985[c]	
1st Ring (r=0.5)[d]								
A_1	0.52	15.0	0.250	63	69	122	133	1.09
B_1	0.52	"	"	47	62	91	119	1.31
C_1	0.52	"	"	38	46	74	89	1.21
D_1	0.52	"	"	33	39	63	74	1.19
E_1	0.52	"	"	28	55	55	105	1.93
F_1	0.52	"	"	45	65	86	125	1.45
2nd Ring (r=1.5)								
A_2	1.58	17.5	0.218	94	163	60	103	1.73
B_2	1.58	"	"	68	78	43	49	1.14
C_2	1.23	"	"	65	110	52	90	1.71
C_2'	0.35	"	"	14	27	40	76	1.90
D_2	1.58	"	"	49	116	31	74	2.39
E_2	0.92	"	"	42	70	46	76	1.67
F_2	1.58	"	"	91	205	58	130	2.24
3rd Ring (r=2.5)								
A_3	2.62	20.0	0.196	80	152	31	58	1.90
B_3	2.62	"	"	73	114	28	44	1.56
C_3	2.13	"	"	36	69	17	33	1.94
C_3'	0.49	"	"	25	42	52	86	1.66
D_3	2.62	"	"	62	70	24	27	1.14
E_3	1.33	"	"	28	41	21	31	1.48
F_3	2.62	"	"	49	97	19	37	1.96
4th Ring (r=3.5)								
A_4	3.65	22.5	0.180	73	143	20	39	1.96
B_4	3.65	"	"	58	83	16	23	1.44
C_4	2.75	"	"	27	62	9.9	22	2.26
C_4'	0.90	"	"	23	69	26	77	2.96
D_4	3.65	"	"	68	116	19	32	1.70
E_4	1.97	"	"	21	31	11	16	1.46
F_4	3.65	"	"	83	157	23	43	1.88
5th Ring (r=4.5)								
A_5	4.72	25.0	0.165	66	90	14	19	1.36
B_5	4.72	"	"	72	119	15	25	1.66
C_5	2.81	"	"	29	57	10	20	1.98
C_5'	1.91	"	"	20	31	11	16	1.55
D_5	4.72	"	"	68	128	14	27	1.89
E_5	--	"	"	--	--	--	--	--
F_5	4.72	"	"	53	144	11	30	2.69
Edges								
L	4.45	27.5	0.152	54	158	12	36	2.95
M	4.92	"	"	66	109	13	22	1.65
N	2.95	"	"	20	44	6.8	15	2.22
O	4.35	"	"	35	120	7.9	28	3.48
P	2.00	"	"	31	73	16	37	2.36
Periphery								
V	10.60	30.0	0.141	59	134	5.6	13	2.26
W	14.60	"	"	49	98	3.3	6.6	2.00
X	9.40	"	"	68	138	7.2	15	2.03
Y	9.40	"	"	93	258	9.9	27	2.77
Z	14.60	"	"	135	294	9.2	20	2.17
Total	147.46	--	--	2301	4346	--	--	--

[a] A subtraction of area is made in zones containing a large portion of a river. The Potomac River divides sector C into two parts, C and C'.

[b] The emission factor was obtained from Figure 1.

[c] Assumes no control of emissions.

[d] The value for the radius r is the distance from the center of the grid to the midpoint of each of the five concentric rings.

and the next density category increases about 2-1/2 times. Thus the doubling of the mean emission density comes about not so much because emissions in the high-density zones grow greater but because so many zones with lower emissions become higher density zones.

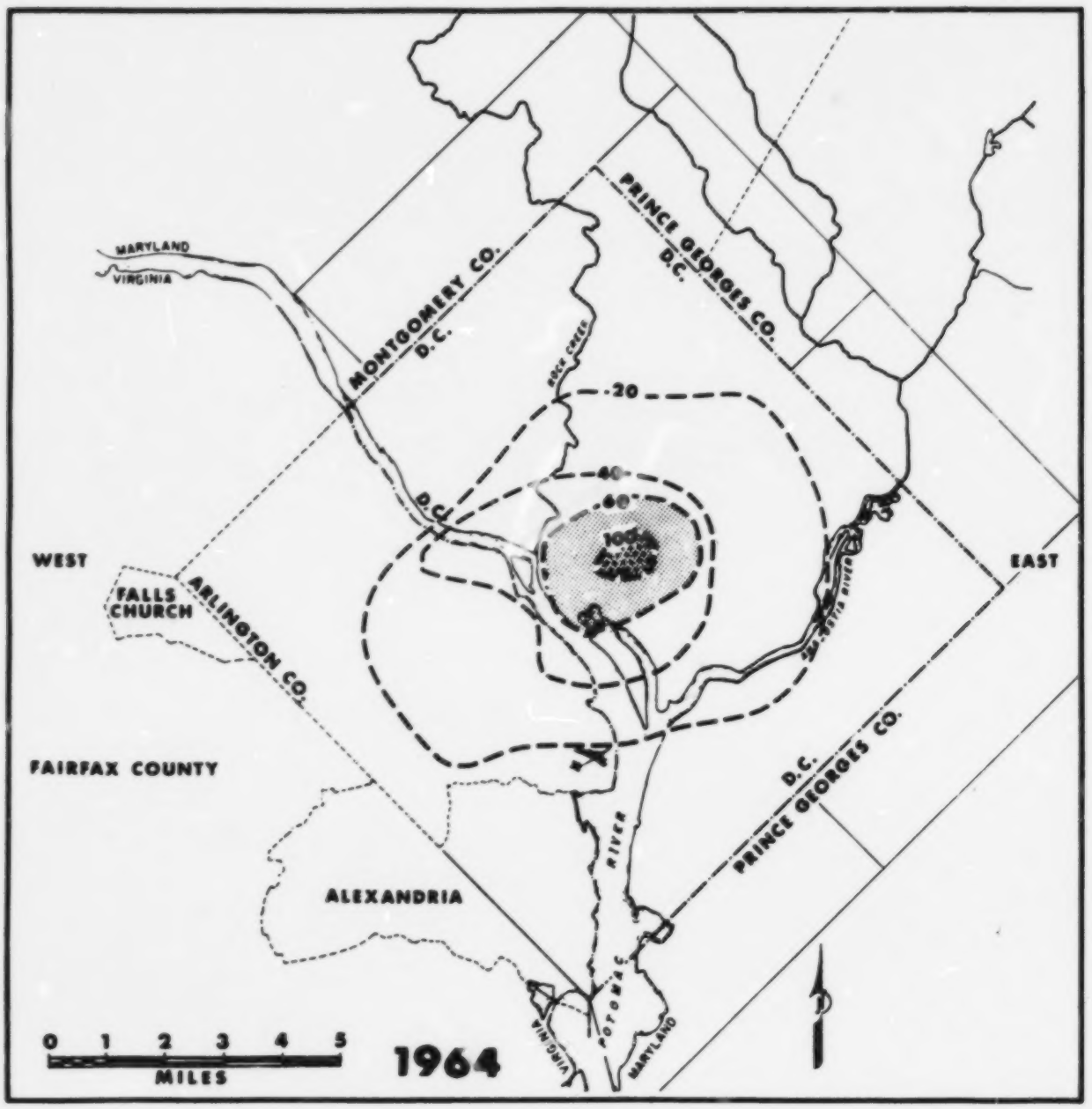
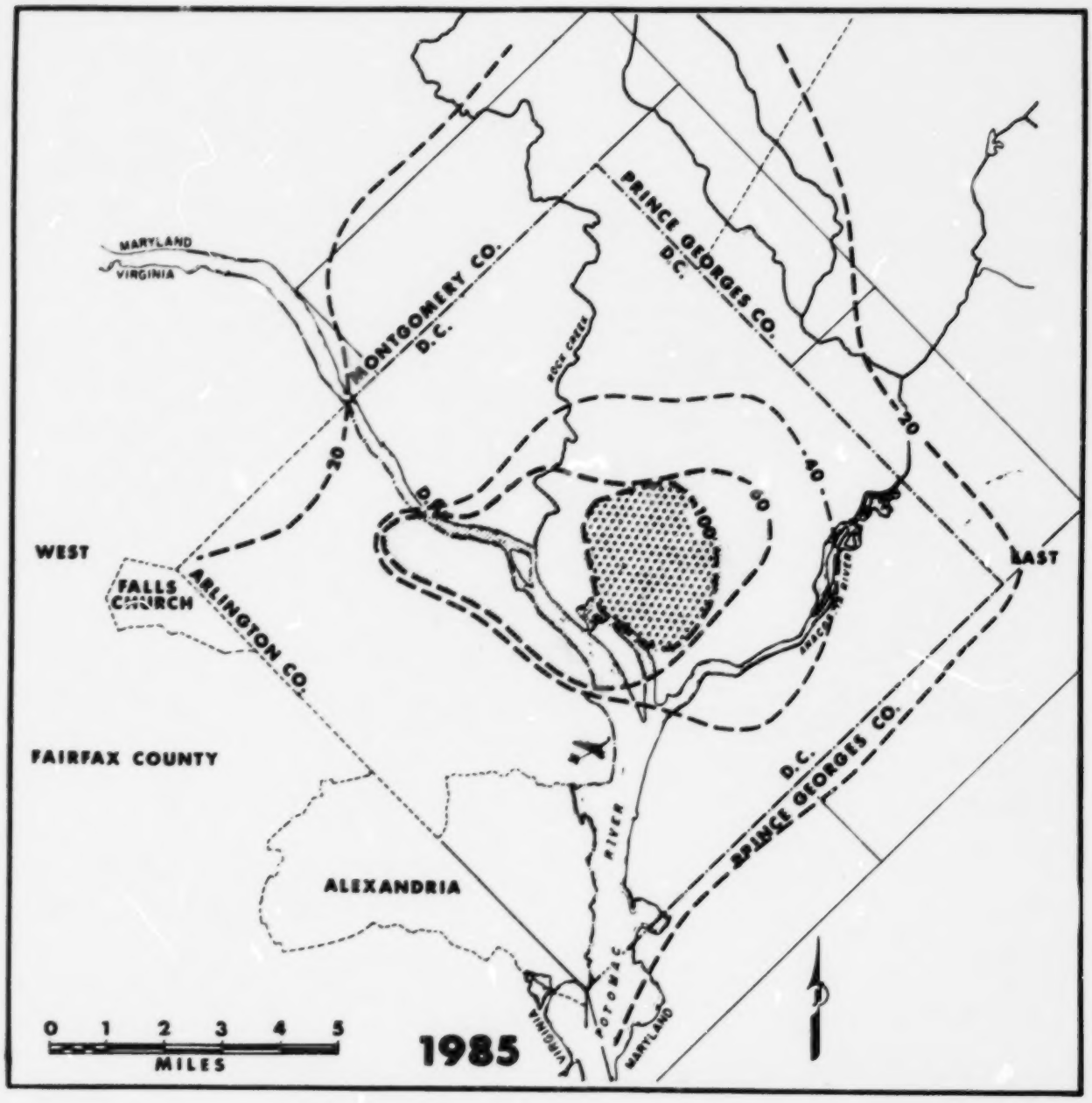


Figure 3. Emission density isolines, 1964, left;

Figure 4 illustrates the growth trends in another way. The growth factors from the last column of the emissions inventory (Table 1) are shown listed on the zones of the inventory grid. Inspection shows that the growth in emission densities forms a definite pattern. Little relative growth takes place in the center of the city, whereas considerable growth occurs in zones far from the center of town.



1985, right (1,000 pounds CO per day per mi).

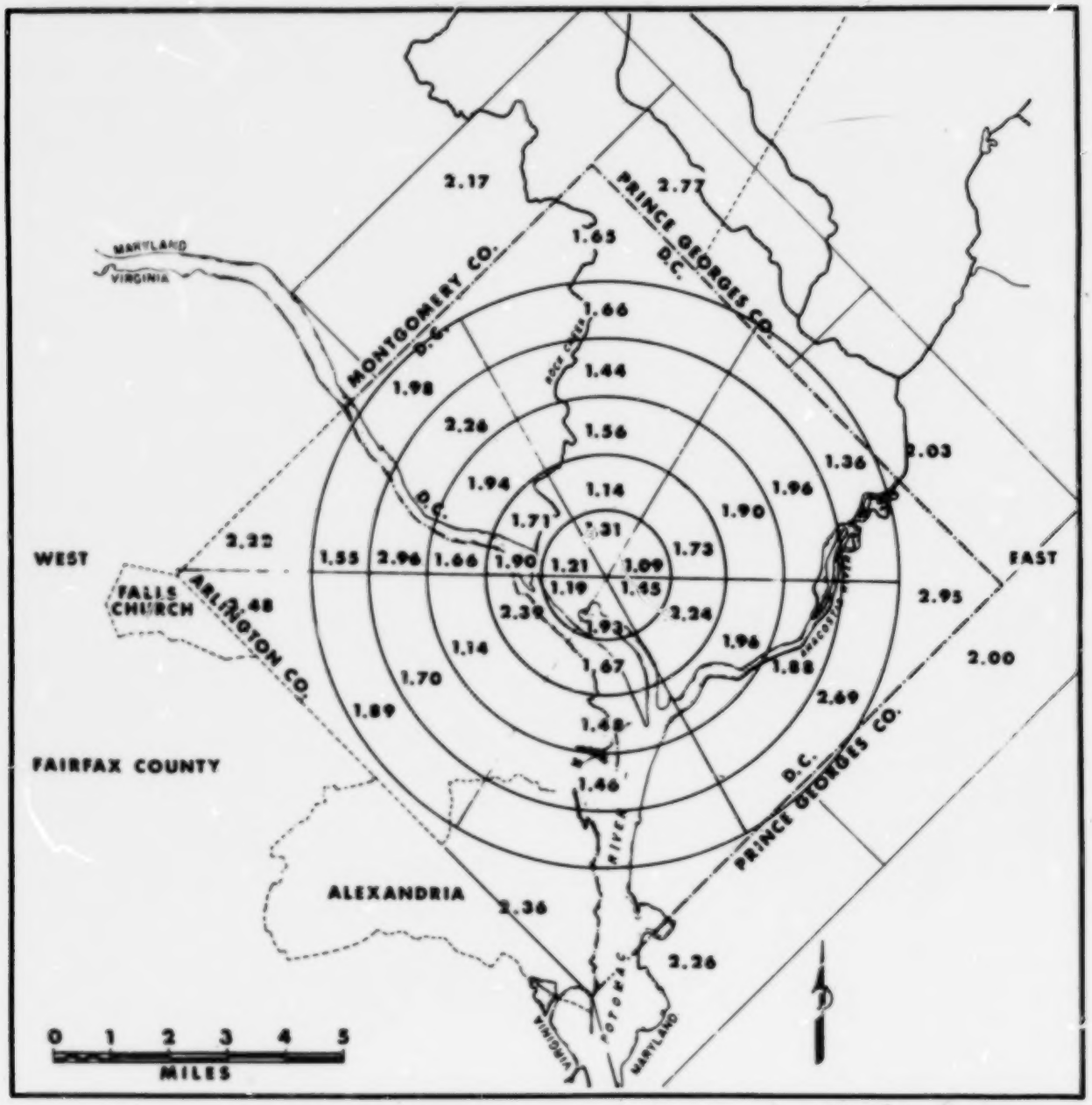


Figure 4. Emission density growth factors for Washington Metropolitan Area—1964-1985.

For example, the emission zones A_1, B_1, and C_1, which comprise most of the downtown shopping area, have an average growth factor of 1.20, or a growth in emission density of 20 percent. By comparison, the outlying park and residential area of zone B_5 has a projected growth factor of 1.66, or an increase of 66 percent; the growth factor in the far-out suburban zone Z is 2.17, indicating an increase in emission density of 117 percent. Thus, the greatest percentage growth for Washington, D. C., occurs in the outskirts rather than in the downtown regions.

That this is a fairly general trend for Washington can be seen from Figure 5, in which all the growth factors in each of the five concentric rings have been averaged and plotted (dotted line). Since the rings are uniformly spaced, the abscissa is also a measure of radial distance from the grid pattern's center. Clearly, the mean growth factor tends to increase with distance, ranging from 1.32 to 2.46. The other two curves in Figure 5, which show the mean emission densities,

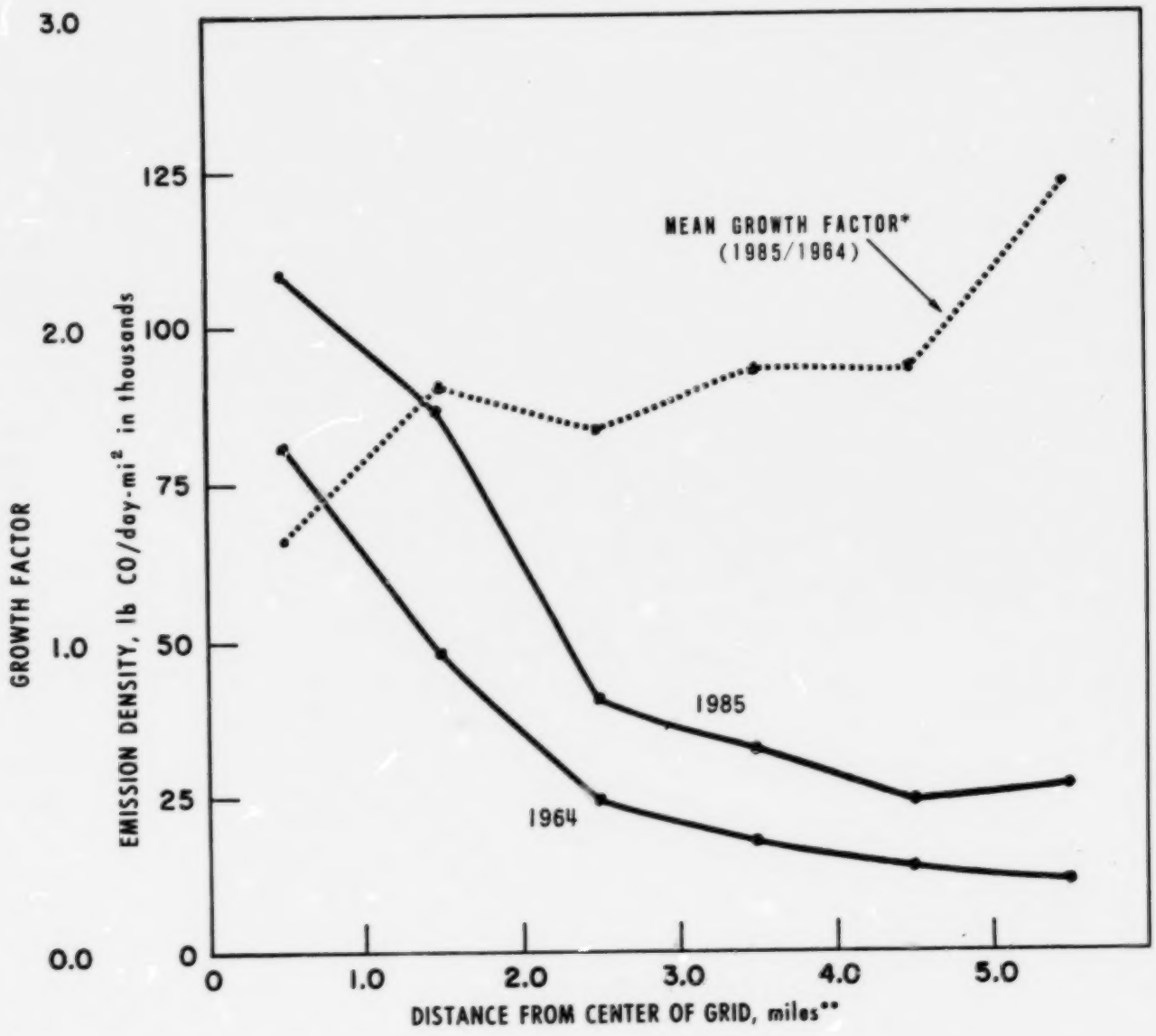


Figure 5. Emission density profiles from Washington, D.C.

*The average of all growth factors within a ring

**Distance is measured from the center of the grid to the midpoint of a ring.

suggest an explanation for this trend. Percentage increases will be greater in the outlying areas because the 1964 densities are relatively small in these regions, and any increase means a large percentage growth. The absolute increase tends to decline with distance, but not so much as the emission densities themselves. Consequently, the absolute increase shows up as a much larger percentage growth in outlying regions when compared with downtown regions. It is important to note that although the emission densities are lower in the outer rings, these rings contain more area than do the inner rings and thus account for a greater share of the total CO emitted.

The fact that in Washington some emission densities in the distant areas may more than double while downtown densities increase relatively little may be further explained by returning to the traffic data from which these figures were derived. The growth factor showing the growth in emission densities from 1964 to 1985 also represents the growth in traffic densities -- vehicle-miles per unit area -- from 1964 to 1985.* Perhaps the fractional increase in traffic flow is less in the downtown areas because the central regions of the city reach a kind of "saturation level" beyond which further relative growth is limited. Most of the increase occurs in the surrounding areas, where traffic is sparser and greater development can yet occur.

If such a saturation density does exist, we would expect to find it in zones where there is both extremely high traffic density and a unity growth factor. Figure 6 shows the traffic density profile for the sector of the Washington grid with the highest traffic densities, sector A. The growth factor in the innermost zone is almost unity (1.09). This indicates a saturation level between 500 and 550 thousand vehicle-miles per day per square mile. However, the fact that there were many variations from zone to zone suggests that more cases should be examined before generalizing about the magnitudes. Note, for example, that the growth factor for sector A declines at the 4.5-mile mark, an exception to the general trend.

Figure 7 shows a map of traffic density growth factors for the Chicago metropolitan area similar to the Washington growth factors shown in Figure 4. Data for 1956 and 1980 were supplied by the Chicago Area Transportation Study. In conducting the Chicago study, authorities divided the city into many small squares to form a rectangular grid. When grouped properly, the squares form an almost concentric pattern with 7 "sectors" and 8 "rings." The overall growth pattern shows an important similarity to that of Washington: zones near the central business district show little relative growth--or even an occasional decline--while zones in the outskirts show considerable increases. Since the study area in Washington is much smaller than that in Chicago, the patterns for the two cities are not strictly comparable. In addition, the individual zones in Chicago are larger, and this may tend to mask particular variations. In spite of the greater size of Chicago, the two cities are similar in that the increase in vehicle-miles is about the same in both--92 percent in Chicago and 94 percent in Washington.

*The growth factor for emission densities is the same as that for traffic densities in Washington because the 1964 and 1985 average velocities were assumed to be the same.

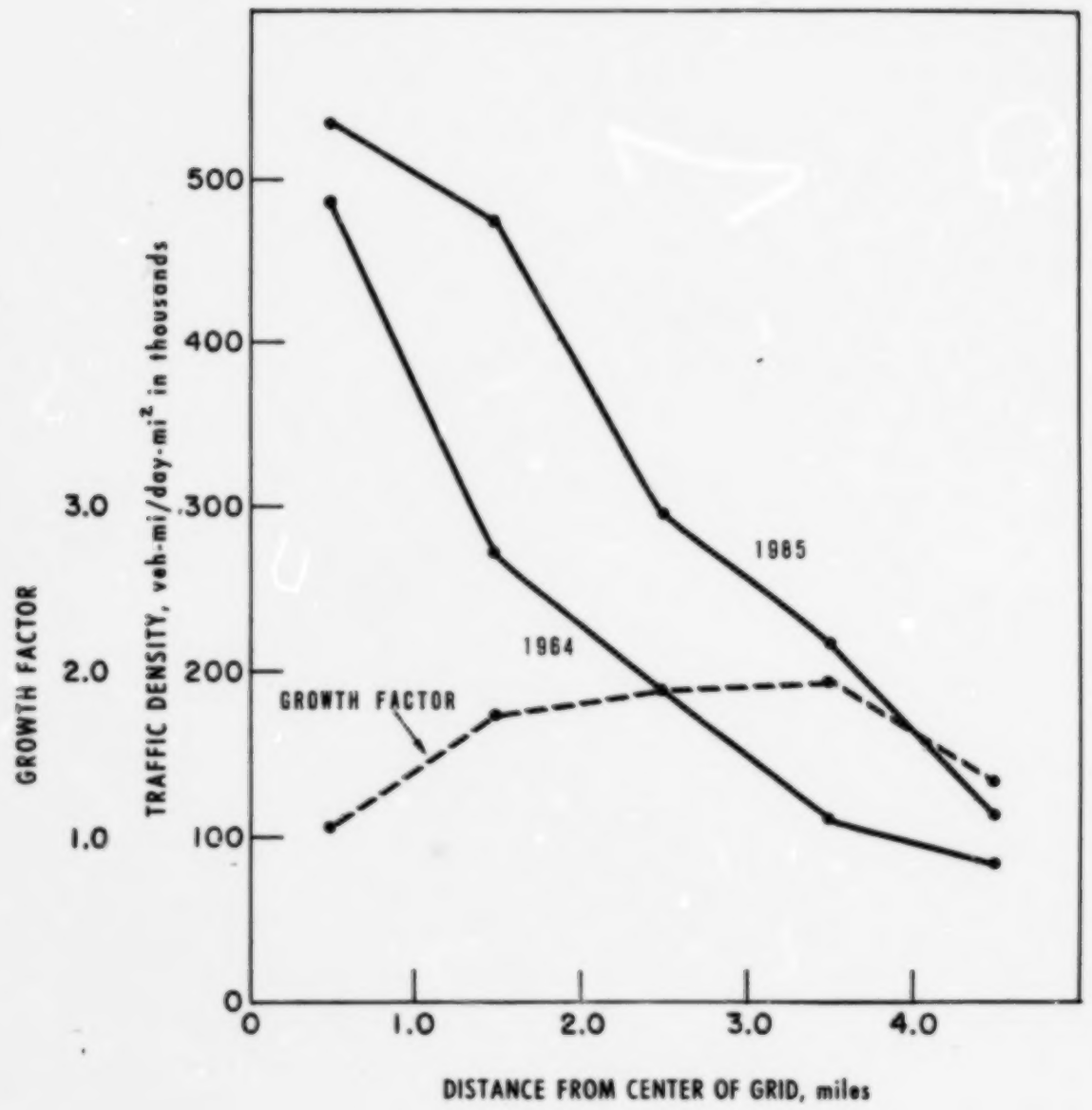
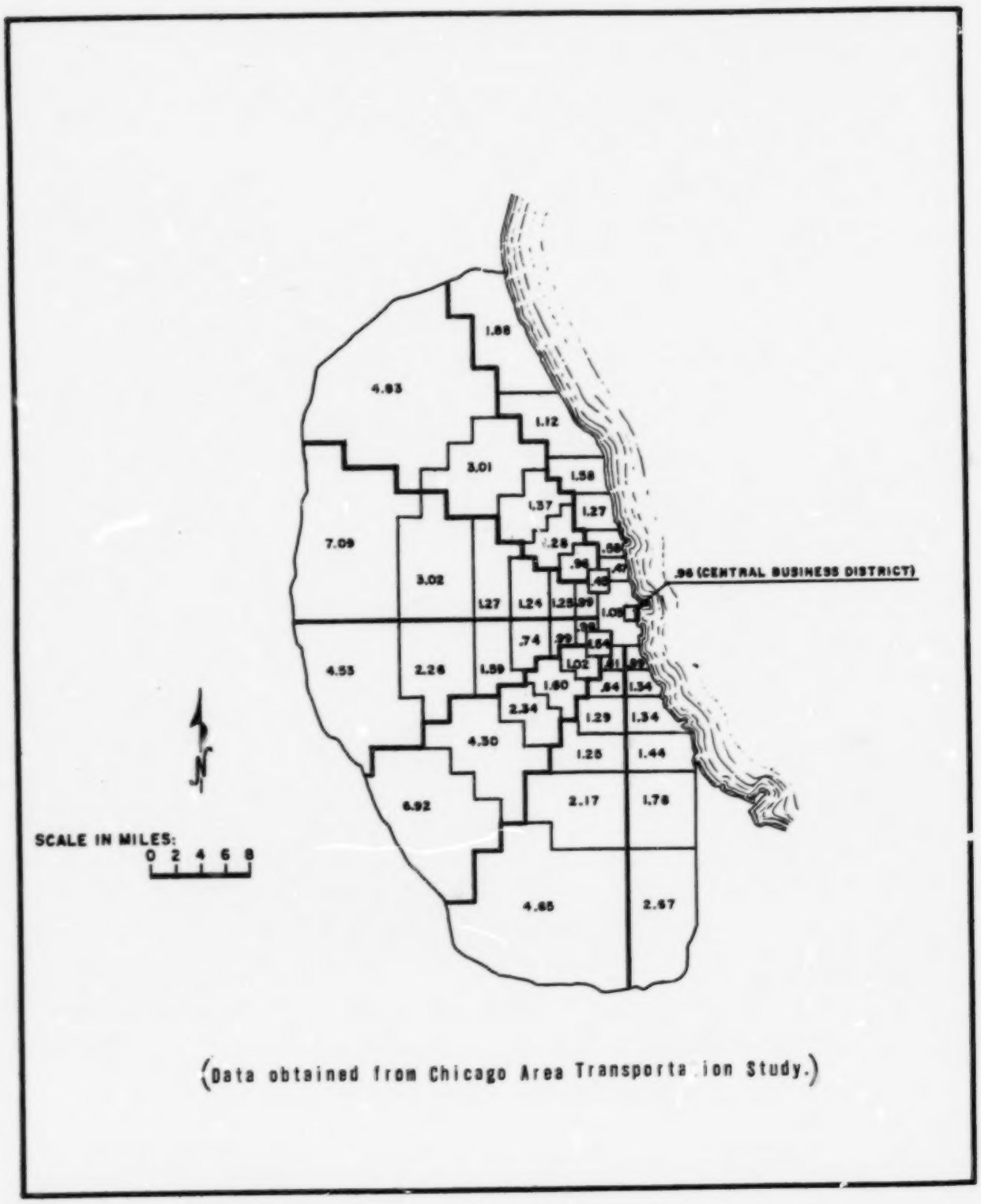


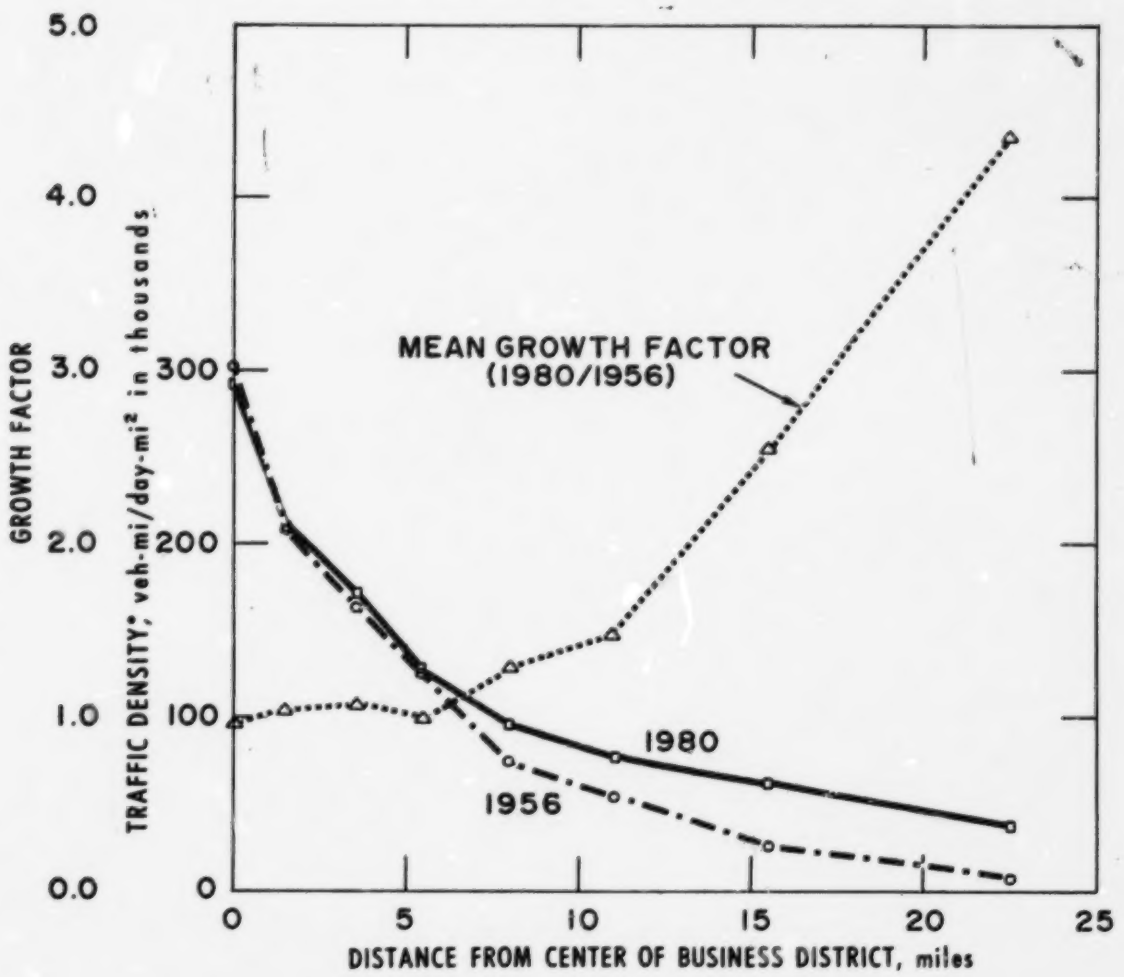
Figure 6. Traffic density profiles for sector A only.

Figure 8 shows the mean traffic densities for Chicago. Although no growth takes place within 5 miles of the center of town (unity growth factor), traffic densities fall off greatly with distance in this region. This is contrary to the concept of a single saturation level applying in such regions, and it implies the concept may be oversimplified. A better hypothesis suggested by the Chicago data is that an "optimum traffic density profile" is reached, after which traffic densities do not change appreciably over time. This happens first at the center of the city and then spreads. Again, this is speculation, for it is obviously necessary to look at the pattern of growth in more cities to make a valid generalization.



(Data obtained from Chicago Area Transportation Study.)

Figure 7. Traffic density growth factors for Chicago Metropolitan Area — 1956-1980.



*Assumes 86% of the traffic occurs on tollways, expressways, and arterial streets.

Figure 8. Traffic density profiles for Chicago.

Regardless of the exact pattern of growth, there is a definite tendency for traffic densities (and hence emission densities) to grow much more in the outlying regions than they do in the downtown areas in both Washington and Chicago. Since the outskirts of a city account for a much larger area than do the downtown regions, the more significant increase in the city's total emissions takes place in the outskirts and not in the downtown areas.

Annual Concentrations

To calculate the mean annual concentrations of carbon monoxide in Washington, D. C., four receptor sites were selected -- three in the downtown area and one across the river in Arlington, as shown in Figure 9. One of the receptor sites

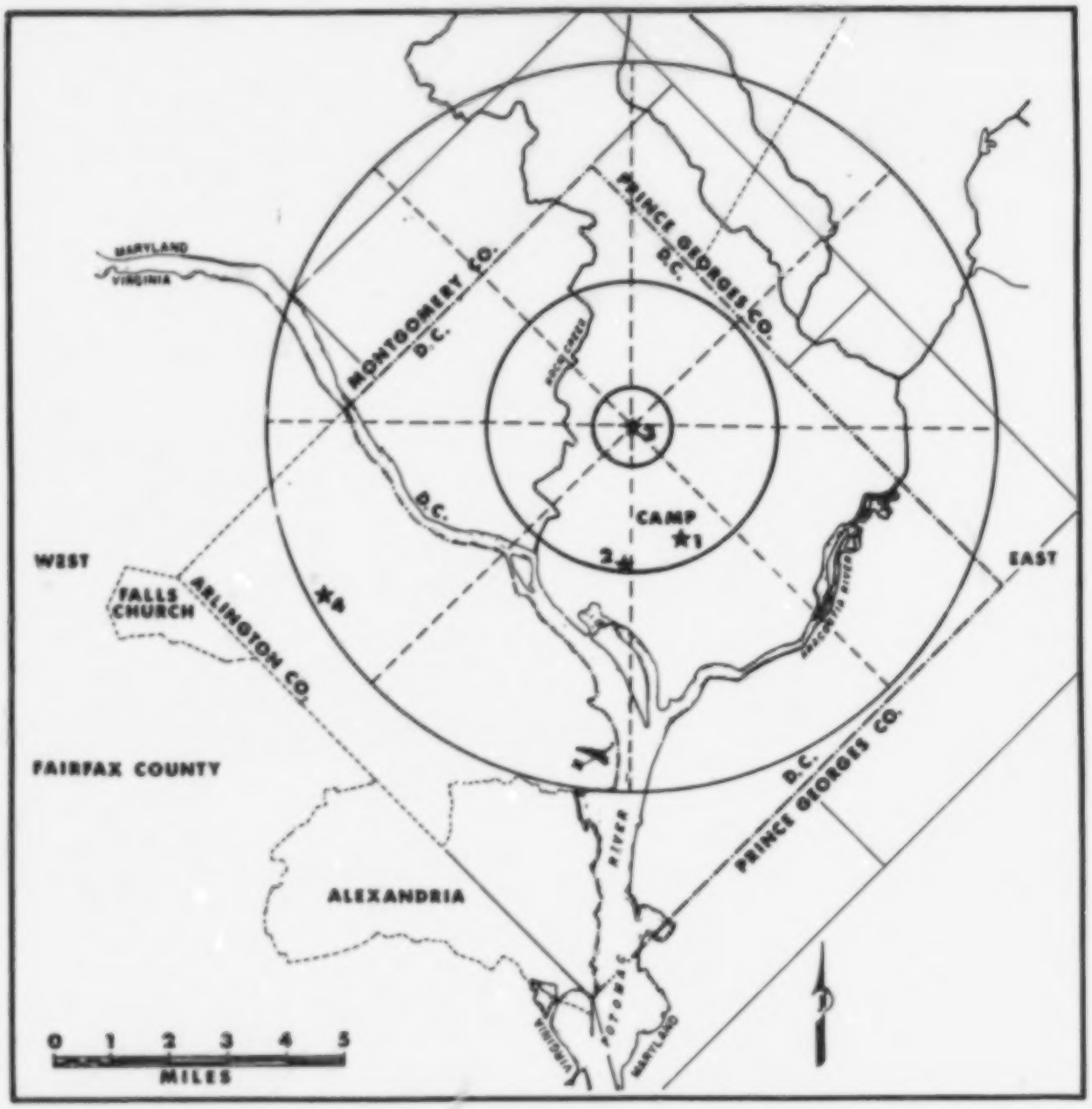


Figure 9. Locations of the four receptor sites (overlay included).

(site 1) was chosen to coincide with the location of the Continuous Air Monitoring Program (CAMP) station operated jointly in Washington by the National Center for Air Pollution Control of the Public Health Service and the District of Columbia Department of Public Health. The station, which provides continuous records of CO concentrations throughout the year, has been operating since 1962.

Figure 9 also shows the diffusion model overlay (circular pattern) centered on receptor site 3. Although both the overlay and the emission inventory grid (Figure 2)

are circular, the two are not to be confused. The former is used as part of the diffusion model to calculate the concentration at a particular point,* while the latter is merely an aid in describing the city's emission patterns. In practice, the overlay was placed over the emissions inventory grid, and the emissions in each of the 24 segments of the overlay were tabulated from the zonal emission densities and the partial areas of the various emission zones enclosed within each segment.

Since emission densities decline rapidly with distance from the city's center (Figure 5), the overlay diameter of 20 kilometers (12.5 mi) is sufficient to cover most of the urban area of Washington when centered on a downtown receptor site. However, it was of interest to calculate the concentration for at least one site that was not centrally located. To examine the appropriateness of using the model with such a site, it is useful to examine the share of the concentration contributed by the three rings of the overlay. Table 2 compares the proportion of the calculated concentration contributed by each of the three rings. Because the third ring contributes a relatively small share of the concentration to sites 1 and 2, we may assume the region beyond may be ignored with little error. This is less true for site 3, and the contribution of the third ring nearly equals that of the other two rings for site 4. This happens because the third ring passes through the heart of the downtown area; it therefore suggests that the emissions immediately beyond the third ring are not negligible. In addition, site 4 is located such that much of the area enclosed lies outside the inventory grid, where no emission data were available; because emission densities were quite low at the outskirts of the city, they were assumed to be zero for this region. Although these assumptions were expected to result in some error in the annual concentrations at sites 3 and 4, the error would be such that the concentrations would be underestimates of the actual values -- especially for site 4.

TABLE 2
Percent Contribution to the Concentration by Overlay Ring
(1964 Data)

Receptor site	Contribution within overlay ring number		
	1	2	3
1	48	43	9
2	60	33	7
3	32	52	16
4	32	39	29

Table 3 shows the street locations of the four receptor sites and the calculated mean annual concentrations at each site. The mean CO concentration measured at the Continuous Air Monitoring Program station for 1964 weekdays was 5.9 ppm, which is 2.8 times larger than the calculated value. Table 4 lists the "street-side concentrations" that have been multiplied by 2.8 to adjust them to values comparable to the CAMP measurement as discussed in the methodology section, page 5. It should be noted that not all of the 2.8 factor is attributable to the street-side adjustment; the fact that the velocities chosen for Washington were rather high has already

*For a full discussion of the annual diffusion model and its application, see Appendix A.

led us to expect calculated values that are underestimates, as was discussed on page 8. The ambient street-side concentrations for 1985 range from 2.2 ppm to 10.9 ppm; however, as mentioned previously, the increase of 1985 values over 1964 values is thought to be more valid than the actual magnitudes of the values, because few of the assumptions underlying the approach are likely to change between 1964 and 1985. Thus Table 4 includes the ratio of the 1985 calculated concentration to the 1964 figure. Listed also is the emission growth factor -- the ratio of 1985 to 1964 emission density -- for the zone in which the receptor site is located. This permits a comparison between the growth in concentrations and the growth in emissions.

TABLE 3
Calculated Concentrations

Receptor site	Location	Mean annual concentration, ppm	
		1964	1985[a]
1	CAMP--1st. and L St., NW	2.08	3.52
2	Pennsylvania and 14th, NW	2.66	3.84
3	New Hampshire and 13th, NW	1.57	2.38
4	16th and Edison St., Arlington	0.50	0.77

[a]Assuming no emission control.

From Table 4 it is clear that the growth in concentrations is much less varied from point to point than the growth in emissions. The growth in concentrations for the four sites ranges from 44 percent to 69 percent, while the growth in emission densities varies over the entire city from 9 percent to 248 percent (see Figure 4). The concentration at site 4, for example, increases 54 percent, while the emission density in that immediate area increases 70 percent. At the same time, the concentration at site 2 -- the most central site -- increases 44 percent, while the emission density for that zone grows only 9 percent. Thus, the mean annual concentrations at all four receptor sites will increase about 50 percent, despite the fact that the total emissions double and that the increase is quite disproportionate throughout the city.

TABLE 4
Street-side Concentrations[a]

Receptor site	Mean annual concentration, ppm		Ratio	Zone	Emission growth factor in zone
	1964	1985	1985/1964		
1	5.9	10.0	1.69	A_2	1.73
2	7.6	10.9	1.44	A_1	1.09
3	4.5	6.8	1.51	B_3	1.56
4	1.4	2.2	1.54	D_4	1.70

[a]Table 3 concentrations adjusted to be comparable to CAMP data; no emission control assumed.

In the downtown areas, where emissions increase relatively little, the concentrations are affected by the increase in emissions in surrounding and more distant zones as a result of transport of carbon monoxide from one zone to another. Thus, the continued expansion in area of urban regions means that downtown concentrations

could go up indefinitely--even with no further increases in downtown traffic--simply because there are greater quantities of carbon monoxide available in the general area to add to the downtown levels.

Since the relationship between concentrations and emissions is linear, the effect of motor vehicle emission control on concentrations can be included simply by multiplying the calculated concentrations by the average percentage control of emissions expected in 1985. Table 5 shows the concentrations predicted if a 50 percent average reduction in motor vehicle emissions is assumed for 1985. Despite this large reduction, levels at the CAMP station decline only 15 percent, and continued growth in traffic beyond 1985 would soon wipe away this margin.

TABLE 5
Street-side Concentrations with Control[a]

Receptor site	Mean annual concentration, ppm		Change, %
	1964	1985	
1	5.9	5.0	-15
2	7.6	5.4	-29
3	4.5	3.4	-24
4	1.4	1.1	-21

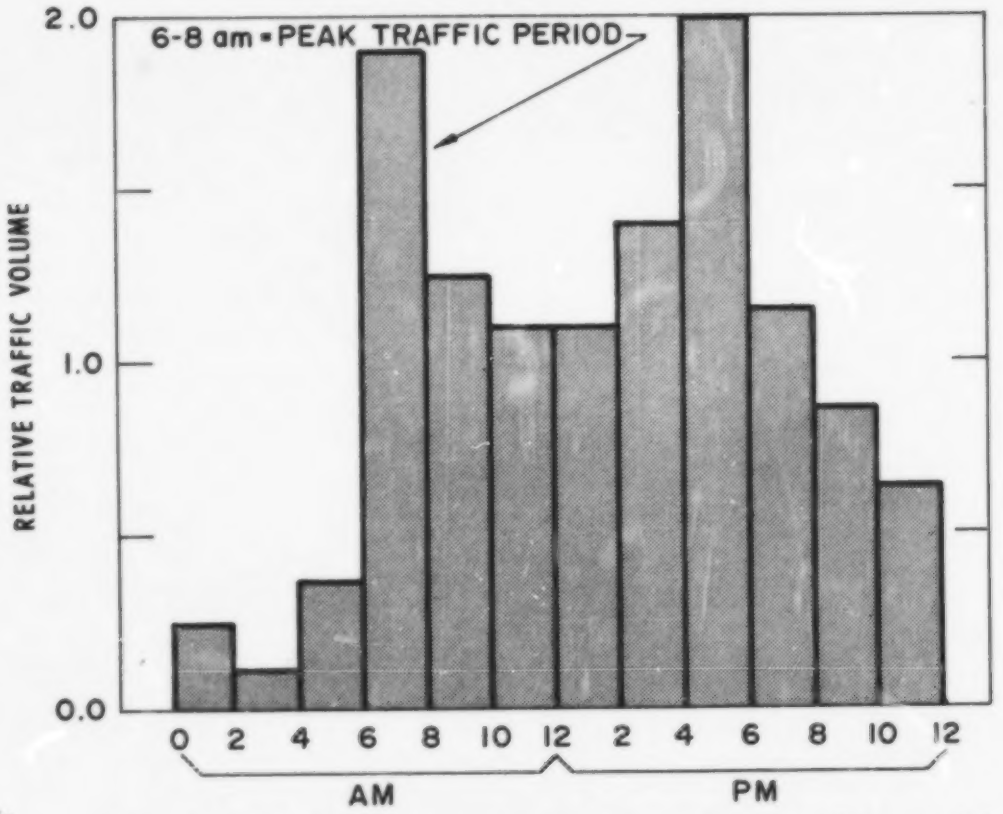
[a]Average reduction in 1985 emissions of 50 percent.

Hourly Concentrations

Although the mean annual concentration is a useful index of overall CO levels, it tells very little about the higher peak values that may occur for short periods of time. Consequently, the average hourly diffusion model developed by Clarke[3] was used to examine the peak-traffic-period concentrations and the diurnal variations. Although this diffusion model can be used to calculate concentrations averaged over as short a period as a single hour, a 2-hour period was selected as adequate.

The diurnal traffic pattern shown in Figure 10 represents factors derived from the city-wide hourly traffic volumes (vehicles/hour) for Washington, D. C. To obtain the emissions for a particular 2-hour period of the day, the emission densities for each zone were multiplied by the factor corresponding to that period.

Figure 11 shows calculated and observed CO concentrations for Sept. 24, 1964, at receptor site 1 (1st and L St., NW, the CAMP site) averaged over 2-hour periods throughout the day. The observed concentrations are measurements at the CAMP station; September 24th was selected as a day of fairly typical concentrations. The shapes of the two curves shown are very similar, although the observed values are uniformly larger than the calculated values. As discussed previously, this difference is expected because of the discrepancy between values measured at a specific point alongside a street and values calculated from emissions assumed uniformly distributed over a large area. The curves do not have the same shape as the traffic factors of Figure 10 because the meteorological conditions vary from hour to hour.



Each factor is the ratio of traffic volume averaged over a 2-hour period to traffic volume averaged over 24 hours. Traffic volumes pertain to weekdays only and are totals for the city as a whole, including traffic into and out of the urban area.

SOURCE: District of Columbia Department of Highways.

Figure 10. Diurnal traffic factors.

Figure 12 compares calculated and observed concentrations for the 2-hour peak traffic period (6:00 AM to 8:00 AM) on 17 different days scattered between September 1964 and July 1965. For observed concentrations below 12 ppm, a relatively consistent pattern emerges: observed values appear larger than calculated values by an average factor of 2.0. This factor compares well with the adjustment factor of 2.8 used to convert calculated mean annual concentrations to street-side values. A simple factor does not explain the differences for the higher concentrations, and this is probably due to a difficulty in specifying wind speeds accurately. High concentrations usually result when wind speeds are low and the pollutant cannot diffuse rapidly, and at low wind speeds, the wind speed measurements made at a single point (e.g., the airport) are less representative of wind speeds throughout the city than when speeds are high. Consequently, we can expect a better match between calculated and observed concentrations for the lower concentrations than for the higher values.

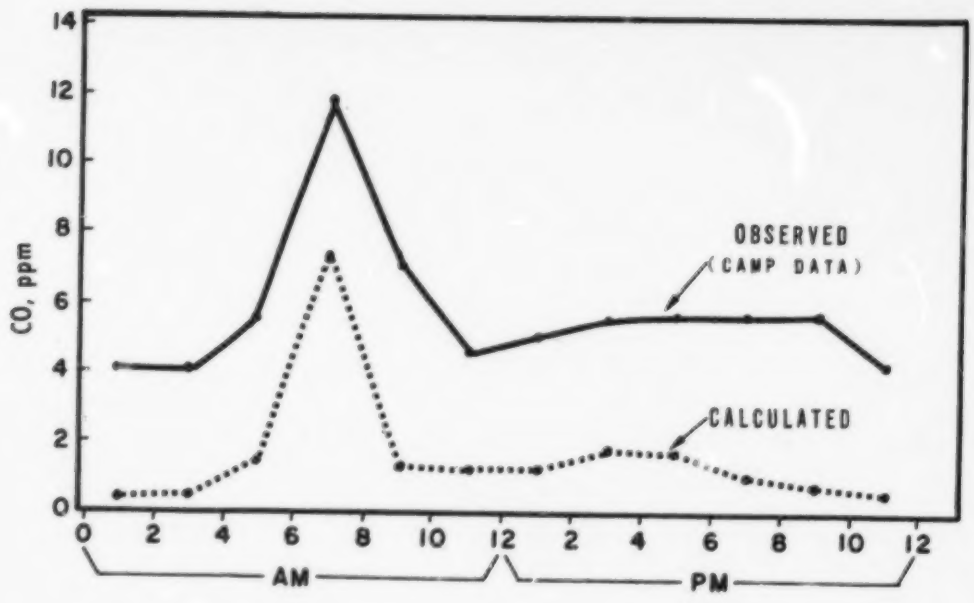


Figure 11. Sept. 24, 1964, diurnal CO concentrations, Washington, D.C.—site 1.

In Figure 13, the peak-traffic-period concentrations for the same 17 days were calculated using both 1964 emission data and 1985 emission data with the 17 sets of meteorological data. Again assuming no control, the 1985 concentrations (2-hour averages) range from 1.6 ppm to 25.4 ppm. Because the ratio of the two coordinates of a point represents the relative growth of the concentration over the 21-year span, the slope of a straight line connecting the point and the origin is actually a growth factor. For these 17 selected cases, the increases range between 38 percent and 120 percent, with an average value of 65 percent. This compares well with the 69 percent growth in mean annual concentration predicted for this receptor site by the annual diffusion model. The fact that some short-term concentrations increase 120 percent without emission control means that these values would go up 10 percent even with 50 percent control. As discussed previously, comparisons in the growth of the calculated concentrations have greater validity than the individual magnitudes of the concentrations, because few of the assumptions incorporated in the model are likely to change over the 21-year span.

Perhaps the most interesting feature of the data in Figure 13 is the tendency for nearly all concentrations to increase by at least 40 percent, regardless of their individual magnitudes. Although there is some tendency for the higher concentrations to increase by a smaller proportion, it is not too pronounced. This suggests that the annual average concentration goes up not only because the lower CO levels are increased, but because the peak concentrations rise as well. Thus, the 69 percent increase in the mean annual concentration comes about because concentrations of all magnitudes shift upward in roughly the same proportion.

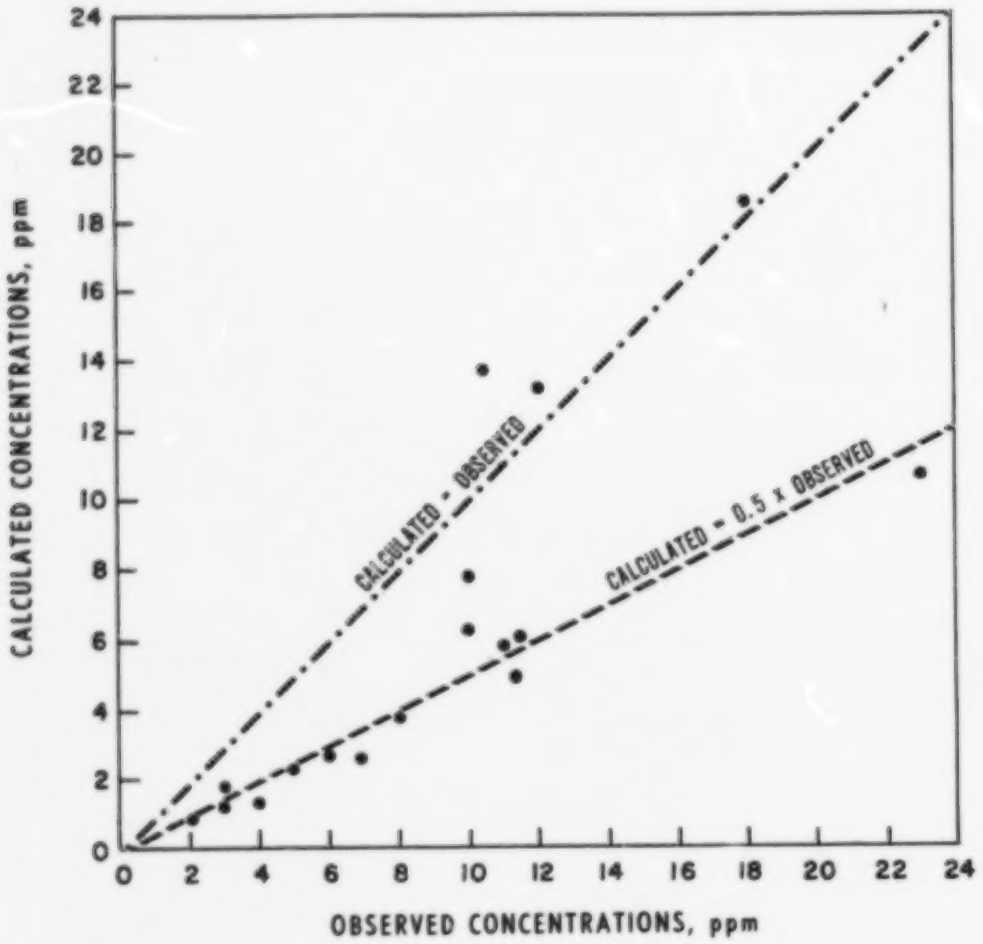


Figure 12. Calculated and observed concentrations for the morning peak-traffic period on 17 days distributed between Sept., 1964, and July, 1965.

SUMMARY

An urban area approach for calculating carbon monoxide emissions and concentrations, using urban traffic data and meteorological diffusion models, was applied to Washington, D. C., both to examine the feasibility of such techniques and to see how changing traffic patterns would affect future levels.

Comparisons of city-wide emissions for 1985 and 1964 showed that, with no emission control, the overall carbon monoxide emitted in the Washington metropolitan area would approximately double in the 21-year span. The percentage increases were found to vary widely throughout the city, however, with the smallest percentage increase taking place in the central regions and the greatest relative

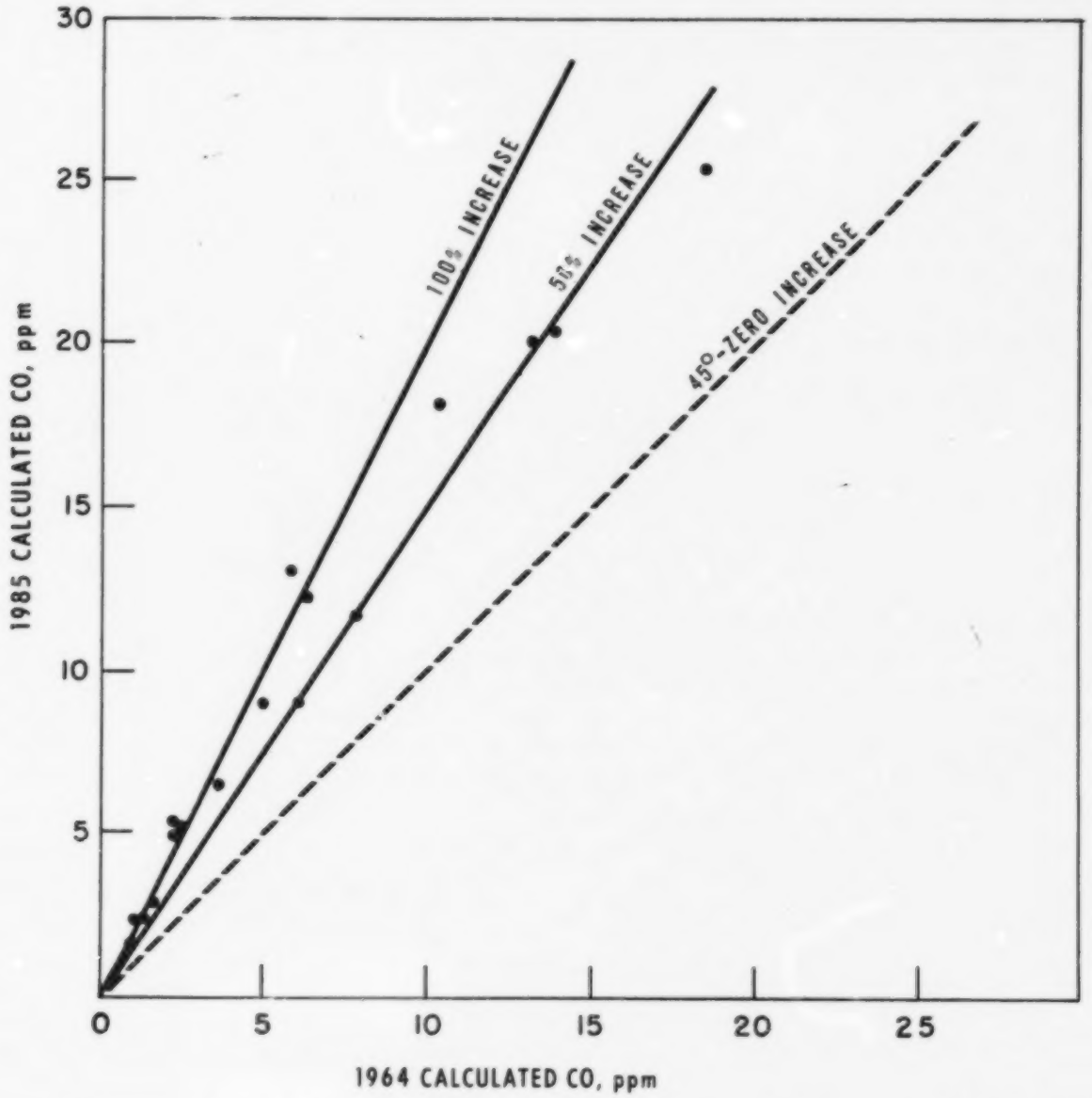


Figure 13. 1985 vs. 1964 peak-traffic period concentrations calculated for site 1, Washington, D.C.

growth occurring in the outskirts of the city. Examination of the traffic patterns of Chicago indicated that the same general pattern of emission growth applied, suggesting that it may be common to most urban areas. It means that the regions with the highest emission densities tend to enlarge in area, growing from the center of the city outward.

Application of an annual diffusion model permitted calculation of mean annual concentrations for 1964 and 1985 at four selected points within the Washington study area. Comparison of calculated and observed concentrations at one site showed good

agreement, considering the anticipated difference between overall average levels and measurements influenced by a particular street. The increases in the calculated concentrations, in the absence of emission control, ranged from 44 percent to 69 percent over the 21-year period. According to the results, however, these changes came about not because of traffic increases in the immediate area of the receptor sites but because of changes in the overall traffic pattern throughout the city. With 50 percent average reduction in emissions in 1985, the concentrations for the four sites, when compared with the 1964 values, showed declines ranging from 15 percent to 29 percent.

Application of an average hourly diffusion model permitted the calculation of concentrations applicable to shorter time periods, depicting the short-term variations in greater detail. Average concentrations for 2-hour periods throughout a particular day were calculated for a single site. They revealed a distinct morning peak, and the shape of the diurnal pattern agreed well with that of observed levels.

To assess the possible increases in morning peaks, the concentrations during the 2-hour morning peak traffic period were calculated both for 1964 and 1985, using meteorological data for 17 selected days. The 1964 results showed good correspondence with observed values, differing by roughly the same expected factor encountered in the mean annual concentrations and attributable to the difference in the circumstances for which the values apply. In the absence of emission control, the 1985 morning peaks ranged from 1.6 ppm to 25.4 ppm. These values represented increases ranging from 40 percent to 120 percent over 1964 calculated values, with an average increase of 65 percent. This suggests that the 69 percent increase in the mean annual concentration calculated for this site with the annual diffusion model resulted from increases in short-term concentrations of all magnitudes and not just from increases in a certain range of magnitudes. Consequently, the peak concentrations do not appear to reach an upper-limit but increase along with the minimum and average values. With 50 percent emission control, some peak values still increase by as much as 10 percent for certain meteorological conditions.

IMPLICATIONS

This study has demonstrated the feasibility of an urban area approach for treating pollution from mobile sources, and has indicated the way in which traffic patterns and meteorological conditions affect concentrations. It has raised several questions, however, each of which opens a new area for possible future study.

The tendency for the high emission densities to spread--in the absence of possible control measures--implies that more people would spend more hours living and working in regions subjected to maximum concentrations. This points to the need, therefore, to examine not only the air quality levels but to look at the variation in population densities in the urban area, considering the changes from year to year as well as the population patterns for different hours of the day.

The fact that 50 percent control in 1985 brings only a 15 percent reduction over 1964 concentrations at the Washington CAMP station, with no reductions in some

short-term peak values, demonstrates the need to examine the entire urban area, since concentrations are determined more by the total traffic pattern than by changes at particular points. It would therefore be very interesting to look at a number of cities to determine whether the same patterns that apply in Washington apply elsewhere. If more cities are studied, it would be beneficial to adapt the approach to the computer, incorporating changing traffic patterns, meteorology, and population trends as part of a larger model for use in urban planning.

A final point of importance is the need to examine the various components that make up a concentration measured in an urban area. Because concentrations are very high in the immediate vicinity of vehicles traveling a given street, measurements made at the edge of the sidewalk (i.e., at the CAMP station) are certainly not representative of the concentrations to which people in the vehicles are exposed. Indeed, the concentrations that are most realistic from the standpoint of commuter exposure may be several times greater than those measured by streetside sampling probes. In addition, some share of the concentrations measured in urban areas may be contributed from other cities by the long-distance transport of the pollutant. Although this urban background component may be small at present, the great urbanization likely to take place in areas such as the eastern coastal region, for example, could result in very significant increases. Thus there is the need to treat each component separately, examining in detail the circumstances responsible for it.

In addition to refining and building upon the urban area approach, therefore, future studies should look both at the smaller environments within the city and at the larger picture involving many cities.

ACKNOWLEDGEMENT

Grateful appreciation is expressed for the guidance and consultation provided by D. A. Lynn, Data Analyst, and Raymond Smith, Chief, Air Quality and Emission Data Branch, National Center for Air Pollution Control.

It should be noted that author John F. Clarke is with the Air Resources Field Research Office, Environmental Science Services Administration, U. S. Department of Commerce, Cincinnati, Ohio.

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APPENDIX A

The Calculation of Mean Annual Concentrations

The Development of the Model

The generalized Gaussian diffusion equation, equation (1), describes the concentration resulting from a point source as following normal distribution in both the horizontal and vertical directions as measured from the plume centerline (Figure A). It assumes the source is continuously emitting and that total reflection from the ground takes place.

$$X = \frac{2Q}{u} \cdot \frac{\exp\left(-\frac{H^2}{2\sigma_z^2}\right)}{\sqrt{2\pi}\ \sigma_z} \cdot \frac{\exp\left(-\frac{y^2}{2\sigma_y^2}\right)}{\sqrt{2\pi}\ \sigma_y} \qquad (1)$$

where X = pollutant concentration (grams per cubic meter)

Q = pollutant source strength (emission rate, grams per second)

u = wind speed (meters per second)

H = effective height of source (meters)

y = distance from plume centerline in horizontal direction (meters)

σ_y = standard deviation of the distribution of pollutant concentration in horizontal direction (meters)

σ_z = standard deviation of the distribution of pollutant concentration in vertical direction (meters)

The sources in this study are automobile tailpipes, which are numerous, widely distributed, and mobile. Since it is impossible to deal with each source individually, it is necessary to assume the sources are uniformly distributed over an area and to modify the basic equations to treat area sources instead of point sources. In doing so, it is useful first to consider a great number of point sources of equal strength sitting in an even line, as depicted in Figure B. If the spacing were small enough, little variation in concentrations would occur along a line parallel to the row (e.g., dotted line). Thus the concentrations in the y-direction, or cross-wind direction, may be assumed uniform, and the part of equation (1) that represents a normal curve in the y-direction may be replaced by unity. Since the sources lie almost at the surface of the ground, the height H is zero, and equation (1) greatly simplifies to give equation (2), where Q_L is the emissions per unit length (grams per second per meter).

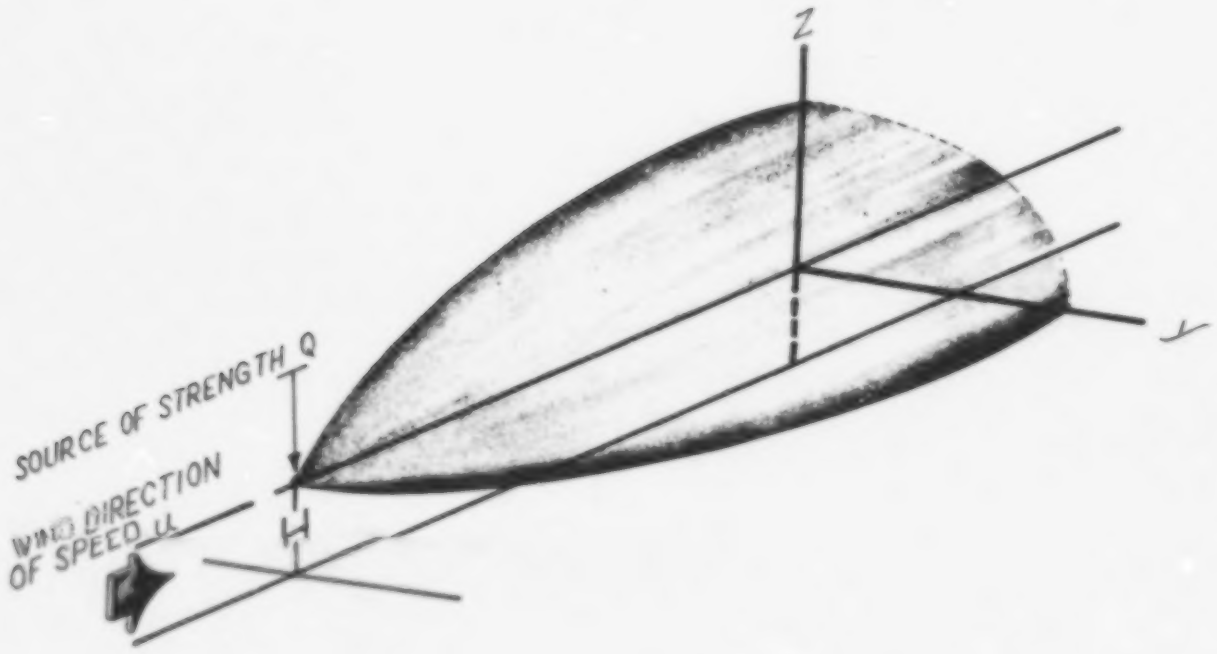

Figure A.

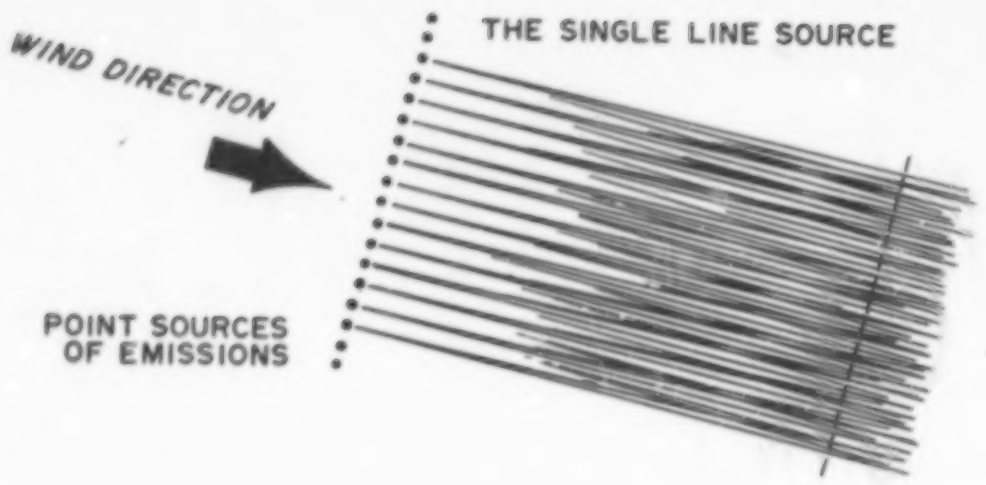

Figure B.

$$X = \frac{2Q_L}{u} \cdot \frac{1}{\sqrt{2\pi}\ \sigma_z} \tag{2}$$

To apply equation (2), it is necessary to know the source strength Q_L, the wind speed u, and σ_z. For time periods ranging from 10 minutes to 1 hour, σ_z can be specified as a function of the stability of the lower atmosphere* and the distance downwind to the receptor. However, calculating a yearly average concentration by averaging many individual hourly concentrations would require far more time and labor than is warranted in view of existing techniques used to specify lower atmospheric parameters. Consequently, the specification of σ_z used by Pooler[4] to calculate mean monthly sulfur dioxide concentrations in Nashville, Tenn., was adopted for this study. According to Pooler, the vertical variance σ_z^2 of the distribution of effluent is assumed expressible as follows:

$$\sigma_z^2 = 2Lu^{\alpha}t^{\beta} = 2Lu^{\alpha-\beta}r^{\beta} \tag{3}$$

where u = a representative wind speed in the surface layer (meters per second)

t = travel time (seconds)

r = travel distance (meters)

α, β, and L = constants

The values of α, β, and L used by Pooler to optimally represent diffusion over Nashville in the winter season are used in the present model, and the reader is referred to Pooler's paper for a more complete discussion of their choice. Substituting Pooler's values (i.e., $\alpha = 0.6$, $\beta = 1.5$, and $L = 0.06\ m^{1.4}$) into equation (3) yields equation (4):

$$\sigma_z^2 = \left[0.347\ u^{-0.45}\ r^{0.75}\right]^2 \tag{4}$$

Substituting this value for σ_z^2 into equation (2) yields a relationship describing the ground level concentration at any distance r from the line source of Figure B:

$$X = Q_L \frac{2.3}{u^{0.55}\ r^{0.75}} \tag{5}$$

*See, for example, Gifford, Reference 6.

To convert this to a relationship applicable to area sources instead of line sources, the area may be assumed to be composed of numerous closely packed rows, as shown in Figure C. Considering each row, or line source, to have infinitesimal thickness, dr, summation is achieved by integrating equation (5) with respect to r. The limits of integration, r_1 and r_2, represent the distances from the receptor point to the boundaries of the area source, and Q_A denotes the emission density for the area. Substituting $Q_L = Q_A\, dr$, equation (5) is integrated directly:

$$X = \int_{r_1}^{r_2} Q_A \frac{2.3}{u^{0.55} r^{0.75}}\, dr$$

$$X = 9.2\, Q_A \frac{r_2^{1/4} - r_1^{1/4}}{u^{0.55}} \qquad (6)$$

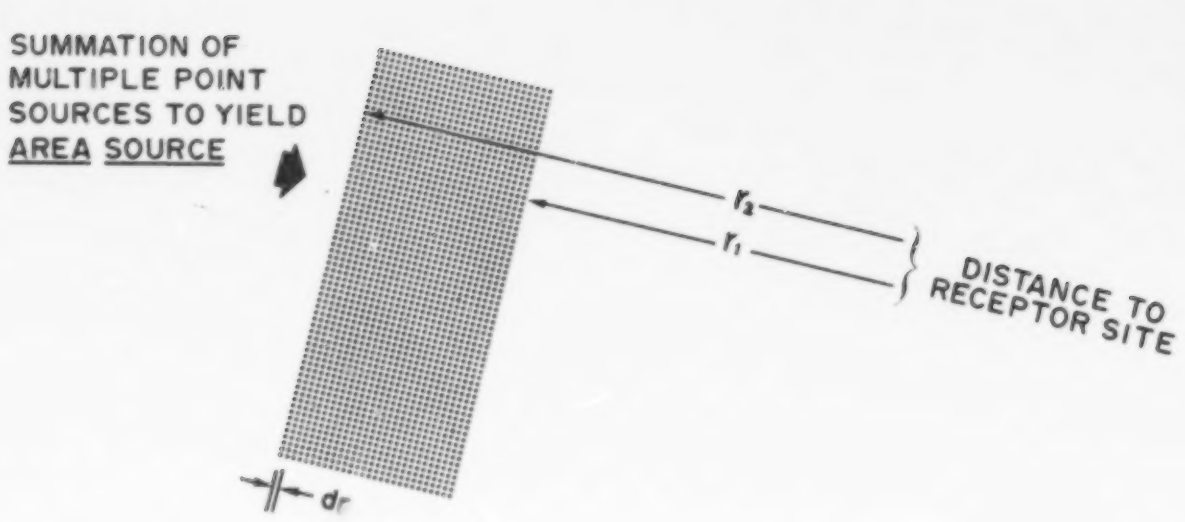

Figure C.

When equation (6) is used to calculate concentrations for an urban area, it is necessary to compensate for the "roughness" caused by buildings and other irregular structures. These effects may be included by assuming that the pollutant

travels over a distance that is a fixed amount greater than the measured distance, producing a "virtual" travel distance. The incremental travel distance takes into account initial turbulence and dispersion of the pollutant caused by buildings, etc.* An incremental travel distance of 100 meters -- previously found applicable in calculating Washington, D. C., oxides of nitrogen concentrations--was thus added to all distances r_1 and r_2. This is shown in equation (7), which expresses the concentration X at a receptor site relative to the area source strength Q_A that lies between distances r_1 and r_2.

$$X/Q_A = \frac{9.2}{u^{0.55}} \left[(r_2 + 100)^{0.25} - (r_1 + 100)^{0.25} \right] \qquad (7)$$

Application of the Model

To calculate the concentration at a specific receptor site, it is necessary to evaluate the contributions made by numerous area sources surrounding the receptor site. This was carried out by adapting the simple receptor-oriented model presented by Clarke.[3] The latter employs a wheel-shaped overlay that can be placed anywhere over a map of emission densities; the concentration at the center of the wheel can then be calculated in a relatively straightforward manner. The overlay used in the model of this study is shown in Figure D. It consists of 3 concentric rings divided into 8 sectors (for 8 wind directions) providing for a total of 24 segments or area sources.

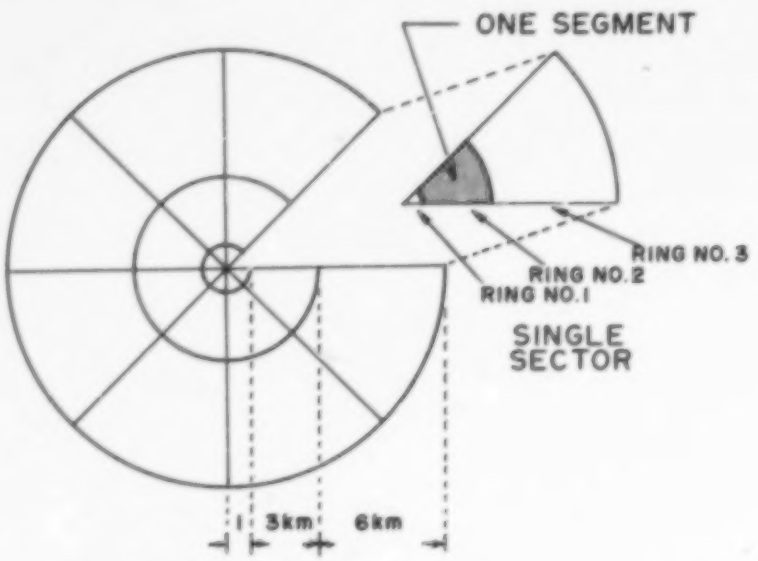

Figure D. Diffusion model overlay.

*See, for example, Pooler, Reference 5.

The overlay was applied by obtaining a value for the emission density in each of the 24 segments when the overlay was centered on a particular receptor site. The relative concentration X/Q_A contributed by a particular segment (bounded by r_1 and r_2) for a given wind speed u can be calculated from equation (7). To obtain the mean concentration contributed by the segment (averaged over a long period of time), the relative concentration can be evaluated for each wind speed, multiplied by the emission density Q_A appropriate to the segment, and summed over all wind speeds. The resulting mean concentration at the receptor site is then obtained by summing overall segments. To reduce the work involved, five wind speeds were selected for this study as representative of five wind speed classes as shown in Table A:

TABLE A
Representative Wind Speeds Chosen for Each Class

Wind speed class, mph	0-3	4-7	8-12	13-18	> 19
Representative speed, mps	0.9	2.5	4.5	6.9	9.6

The frequencies of occurrence of these speeds for various directions were obtained from a U.S. Weather Bureau summary of hourly observations at Washington National Airport for the period 1951-1960.[9]

In practice, the relative concentration for each wind speed class was multiplied by the frequency of occurrence of that class and the results added for the five classes. Then the mean annual concentration at the receptor site was obtained by summing over all segments (over 3 rings and 8 radial directions). Computing the relative concentration appropriate to each ring was simplified by evaluating equation (7) quite generally for the three rings:

Ring No. 1: $$\frac{X}{Q_A} = \frac{23.924}{u^{0.55}} \qquad (8)$$

Ring No. 2: $$\frac{X}{Q_A} = \frac{20.665}{u^{0.55}} \qquad (9)$$

Ring No. 3: $$\frac{X}{Q} = \frac{18.637}{u^{0.55}} \qquad (10)$$

The entire process of calculating the mean annual concentration is shown mathematically by equation (11), in which s denotes the number of the ring and $f_{u,\theta}$ is the fractional frequencies of winds of speed u and direction θ:

$$\bar{X} = \sum_{\theta, s, u} Q_{s,\theta} \left(X/Q_A \right)_{s,u} f_{u,\theta} \qquad (11)$$

To obtain the mean annual concentration at another receptor site, the overlay was moved to that site and the process repeated.

Discussion

It is interesting to examine the effect of source distance on the concentration at a particular receptor site as predicted by the model.

According to the diffusion equations, the concentration that results from a given source decreases rapidly with increasing distance from the receptor. This is shown in Figure E, in which the carbon monoxide concentrations are given as a function of distance for a specified line source strength and a wind of 1 mps. The radii of the three concentric rings of the overlay were originally selected so as to weigh equally the relative concentration each contributed to the receptor site under a specified set of meteorological conditions (Clarke, Reference 3). The effect of the greater distance between the receptor site and the outer ring was compensated for by the greater area of the outer ring. However, the meteorological assumptions for which the overlay was originally designed differ from those used to calculate mean annual CO concentrations, and the relative concentrations for the three rings as evaluated from equation (7) are not exactly equal. Table B shows the share of the relative concentration that each ring would contribute if each ring enclosed the same emission density. With uniform emissions per unit area and no emissions beyond the third ring, 37.7 percent of the calculated concentration would result from emissions within the first 1,000 meters from the receptor site. Emissions from the next two rings would account for 32.7 percent and 29.6 percent, respectively, of the calculated concentration.

TABLE B

Percent Contribution of Each Ring With Uniform Emission Density

Overlay ring	Radii	Relative concentrations	Percent
1	0-1,000 m	$\frac{23.924}{u^{0.55}}$	37.7
2	1,000-4,000 m	$\frac{20.665}{u^{0.55}}$	32.7
3	4,000-10,000 m	$\frac{18.637}{u^{0.55}}$	29.6

In actuality, the emission densities in an urban complex are not uniform. As shown for Washington, the maximum emission densities occur near the center of the city and decrease with distance. Table C shows the percent contribution of each of

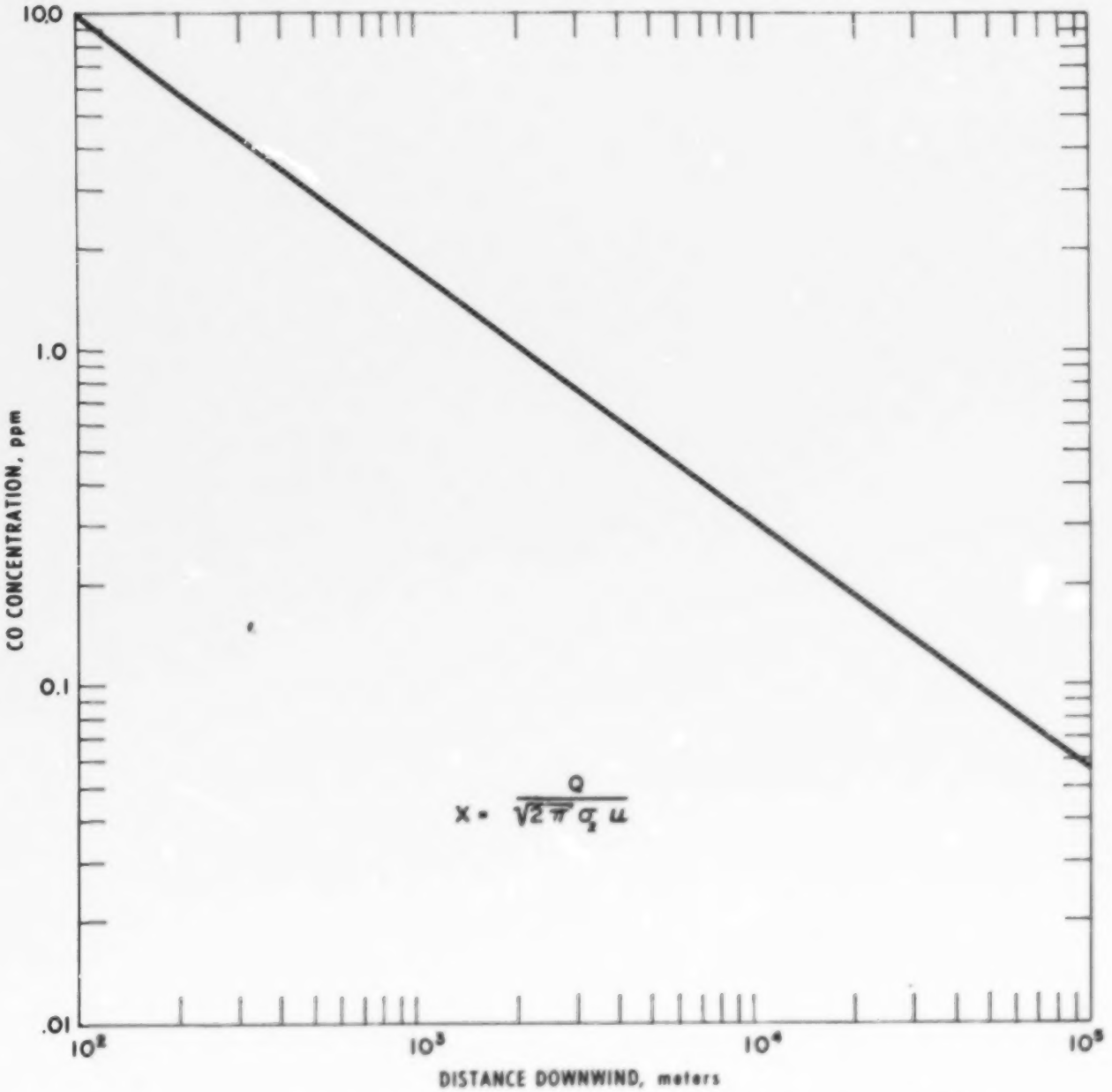

Figure E. CO concentration vs. source-to-receptor distance.

the three rings to the calculated concentration for the four receptor sites in Washington, D. C. For a location near the center of the city, at Pennsylvania and 14th NW, the first ring is predominant. The trend between 1964 and 1985, however, is for the more distant sources in the second and third rings to contribute an increasing share to the resulting concentration, reflecting the greater increases in emission densities in the areas enclosed by these rings. For a receptor site located away from the center of the city, such as that at New Hampshire and 13th NW, the high emission

densities in the downtown areas (ring 2) contribute a greater share than the sources nearby the receptor.

TABLE C
Percent Contribution of Each Ring for Washington, D. C.

Receptor site	Location	Year	Contribution within overlay ring number		
1	CAMP	1964	48	43	9
		1985	50	40.5	9.5
2	Pennsylvania and 14th NW	1964	59.6	33.0	7.4
		1985	52.7	38.6	8.7
3	New Hampshire and 13th NW	1964	31.9	52.2	15.9
		1985	32.8	47.2	20.0
4	Arlington	1964	32.2	39	28.8
		1985	37	37.4	25.6

It is interesting to speculate on the change in concentrations that would come about at a downtown receptor site if emission densities at the outskirts increased to the levels that now apply in the downtown areas, while no further increases occurred downtown. For example, if the emission densities in the second and third rings around the Pennsylvania and 14th NW, receptor site increased to the present value of the first ring (possibly a saturation value), the concentration would increase 58 percent--even though no changes in emissions took place in the first ring. This is a conservative figure, since emission densities of this magnitude in the third ring would mean the area beyond the third ring (i.e., beyond 10,000 meters) could no longer be ignored.

APPENDIX B
Traffic Inventory for Washington, D. C.

Zone[a]	Area,[b] mi^2	Average speed, mph	Daily vehicle miles of travel (DVMT in thousands)		Traffic density (DVMT/mi^2 in thousands)	
			1964	1985	1964	1985
1st Ring (r=0.5)[c]						
A_1	0.52	15.0	254	276	488	532
B_1	0.52	"	189	247	363	476
C_1	0.52	"	153	185	295	357
D_1	0.52	"	130	155	250	298
E_1	0.52	"	114	219	219	422
F_1	0.52	"	179	260	344	499
2nd Ring (r=1.5)						
A_2	1.58	17.5	432	748	274	473
B_2	1.58	"	314	358	199	227
C_2	1.23	"	296	506	241	411
C_2'	0.35	"	64	122	184	349
D_2	1.58	"	223	534	141	338
E_2	0.92	"	192	321	209	349
F_2	1.58	"	420	940	266	595
3rd Ring (r=2.5)						
A_3	2.62	20.0	409	777	156	296
B_3	2.62	"	373	582	142	222
C_3	2.13	"	182	353	85	166
C_3'	0.49	"	129	215	264	439
D_3	2.62	"	315	359	120	137
E_3	1.33	"	143	211	107	159
F_3	2.62	"	252	495	96	189
4th Ring (r=3.5)						
A_4	3.65	22.5	406	795	111	218
B_4	3.65	"	320	461	88	126
C_4	2.75	"	151	342	55	124
C_4'	0.90	"	130	386	145	429
D_4	3.65	"	378	642	103	176
E_4	1.97	"	119	173	60	88
F_4	3.65	"	463	870	127	238
5th Ring (r=4.5)						
A_5	4.72	25.0	399	542	85	115
B_5	4.72	"	434	721	92	153
C_5	2.81	"	176	348	63	124
C_5'	1.91	"	122	189	64	99
D_5	4.72	"	411	777	87	165
E_5	--	--	--	--	--	--
F_5	4.72	25.0	323	870	69	184
Edges						
L	4.45	27.5	353	1,043	79	234
M	4.92	"	435	718	88	146
N	2.95	"	132	293	95	99
O	4.35	"	227	791	52	182
P	2.00	"	204	481	102	241
Periphery						
V	10.60	30.0	422	953	40	90
W	14.60	"	347	694	24	48
X	9.40	"	483	980	51	104
Y	9.40	"	661	1,930	70	195
Z	14.60	"	960	2,084	66	143
Total	147.46	--	12,819	24,846	--	--

[a] Figure 2 shows the locations of each of the zones in the zonal grid.
[b] A subtraction of area is made in zones containing a large portion of a river. The Potomac River divides sector C into two parts, C and C'.
[c] The value of r is the distance from the center of the grid to the midpoint of each of the five concentric rings.

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